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Knowledgeable academic and government scientists assembled at NEPRF on 30-31 August 1982 to discuss coupling of ocean and atmospheric models for 3-15 day numerical prediction. This publication reviews those discussions with respect to the atmospheric model responses to such coupling.

Three forecast time periods were considered: 3, 7, and 15 days; these represented present capability, near term goals, and the ultimate limit of dynamic predictability, respectively. ((continued on reverse))

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Block 20, Abstract, continued.

Three modes of coupling were considered -- weak, non-synchronous, and synchronous -- involving steady state, one-way interactive, and two-way interactive sea surface temperature boundary conditions, respectively.

Key conclusions of the workshop with respect to atmospheric model responses to ocean coupling were:

(1) For three-day forecasts, a carefully controlled SST analysis that is kept fixed through the forecast period (i.e., weak coupling), is probably adequate and surely the most feasible for routine operations. This should be implemented as soon as possible.

(2) Probably for seven days, and almost surely for fifteen days, some form of time dependent SST predictions will aid the atmospheric forecast.

(3) Ultimately, synchronous coupling in which both atmospheric and ocean models respond to each other at every (or at least frequent) time steps will improve seven day and fifteen day forecasts. Improvements in data, stratospheric forcing, and topography representation, however, are all of greater or at least equal importance as ocean coupling to greater forecast accuracy.

(4) There are so many nonlinear interactions in present atmospheric models that thorough study with perfect-prognosis SST patterns is needed before operational implementation of ocean coupling should be considered.

Key conclusions of the workshop with respect to ocean mixed layer model responses to atmospheric coupling were:

(1) Response of ocean mixed layer depth to atmospheric fluxes of momentum and heat is quite direct and rapid (1-2 days). This is particularly true during spring and fall transition periods in the mid-latitudes.

(2) Success or failure of mixed layer prediction is almost completely dependent on atmospheric model prediction of surface fluxes.

(3) Dynamic ocean features such as western boundary currents, mesoscale eddies, etc., are governed by internal ocean dynamics and are nearly independent of atmospheric forcing on the 3-15 day time scale.

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COUPLED OCEAN-ATMOSPHERIC MODELING FOR 3—15 DAY NUMERICAL PREDICTION: A WORKSHOP REPORT

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CONTENTS

1. INTRODUCTION

On August 30-31, 1982 the Naval Environmental Prediction Research Facility (NEPRF) hosted a workshop on Ocean-Atmosphere Modeling for 3-15 Day Numerical Prediction. The key reason for holding this workshop early in the 1980's was to help chart a course of action in the Navy in this area through the 1990's.

The workshop was arranged jointly by NEPRF and the Naval Ocean Research and Development Activity (NORDA), under the sponsorship of the Office of Naval Research (ONR). In this report we present the proceedings and recommendations of that workshop. The lead authors of each successive chapter in this report are A. I. Weinstein, T. E. Rosmond, and S. Piacsek.

The remainder of this introduction starts with a brief description of the relevant physics of air-sea interaction on the 3-15 day prediction time scale. The introduction proceeds with a review of the Navy interest in the problem and a description of the workshop structure and objectives. This introduction concludes with a presentation of the key recommendations that came out of the workshop. Each of these recommendations is supported elsewhere in the body of this report.

Section 2 of this report contains a summary of each workshop participant's presentation. We present the summaries just as each presenter submitted them, in the order they were presented (see program, App. A), with only minor editing by T. Rosmond to keep the format uniform.

Sections 3 and 4 are the most important portions of this report. Here we present the workshop conclusions and recommendations. Section 3 deals with atmosphere modeling, while Section 4 deals with ocean modeling.

1.1 Physics of the Problem

Most elementary meteorology and oceanography textbooks describe global energy budget cycles that include exchanges between the atmosphere and ocean. Dominant among these exchanges are:

(1) Momentum flux from the atmosphere to the ocean caused by wind stress;

(2) Short wave radiant heat flux from the sun, through the atmosphere, to the ocean;

(3) Long wave radiant flux from the ocean to the atmosphere;

(4) Latent heat flux from the ocean to the atmosphere; and

(5) Sensible heat flux in either direction depending on the ocean-atmosphere temperature difference.

Figure 1 is a schematic representation of these fluxes. The evolution of the atmosphere and ocean that results from these fluxes, has been the subject of considerable study over the years.

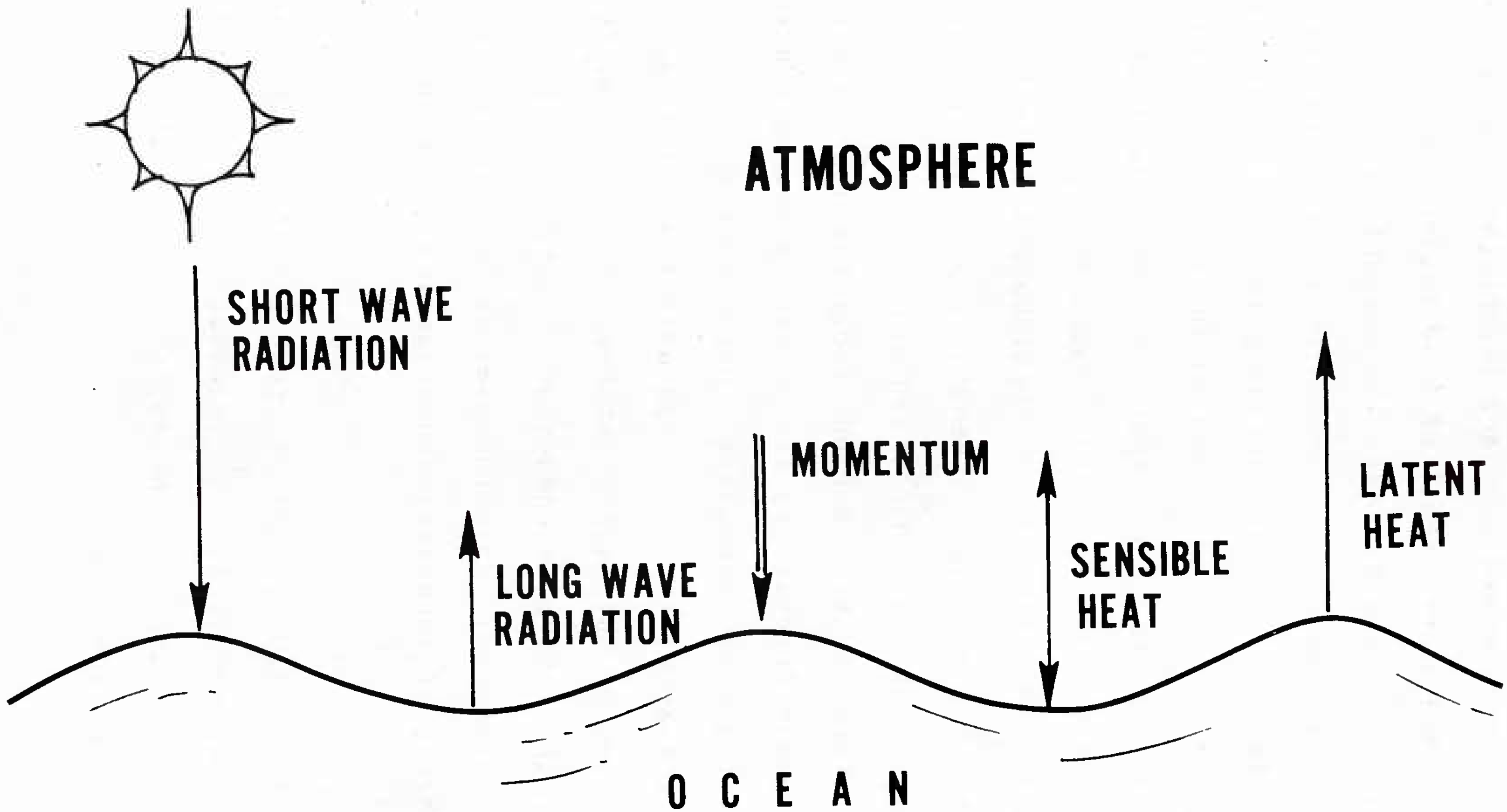

Figure 1. Major energy fluxes between the atmosphere and ocean.

Most treatments of the problem divide both the atmosphere and ocean into well-mixed boundary layers that are in direct contact with each other, and free flow regions above or below, respectively. In the atmosphere the contact layer is called the planetary boundary layer and the region above is called the free atmosphere. In the ocean the boundary layer is called the mixed layer and the region below is called the deep or abyssal ocean. In both fluids, the boundary layers are separated from these free regions above and below by stable layers that are called the low level or marine inversion in the atmosphere and the thermocline in the ocean. Figure 2 is a schematic representation of the indicated ocean and atmospheric regions.

For the forecast time periods under consideration here, 3-15 days, atmospheric forecasters are primarily interested in the evolution of the free atmosphere. Ocean forecasters, on the other hand, are primarily concerned with the mixed layer. The detailed reason for this different focus of attention is beyond the scope of this short introduction . Suffice it to say that different dominant physical processes in the two fluids and different levels of technical understanding are both important.

1.2 Navy Background

Within the broad context of ocean and atmospheric prediction, it is next appropriate to introduce the Navy interest. Navy interest in weather and ocean forecasting dates back to the origin of the service itself.

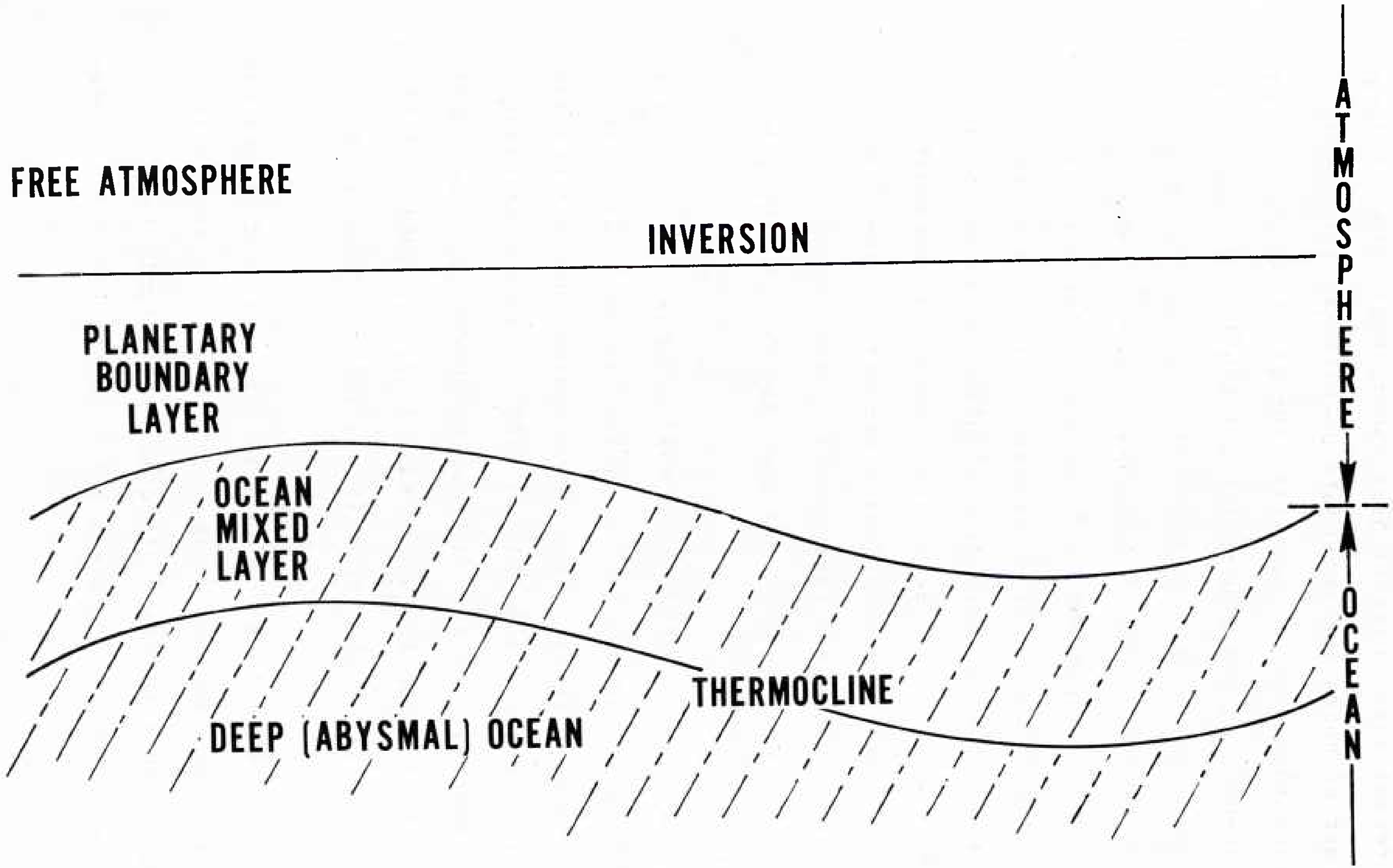

Figure 2. Atmospheric and oceanic regions.

The forecast time frame of Navy operational interest ranges from the order of hours for immediate operations, through days for short term planning, to two weeks for major ocean crossings. Long range prediction and climatological studies, although often used for weapons design and possible strategic planning, are less reliable than actual forecasts for on-site operations.

In this era of expanding main frame computer technology, the best way to prepare three-day to two-week forecasts is to integrate the appropriate equations of atmospheric and ocean physics on a large computer at a single numerical forecast center. In 1976 the Navy undertook a project to develop a modern, worldwide Automated Environmental Prediction System (AEPS) for its Fleet Numerical Oceanography Center (FNOC) in Monterey, CA.

The two keystones of AEPS were what are now called the Navy Operational Global Atmospheric Prediction System (NOGAPS) as described by Rosmond (1981) and a Thermodynamic Ocean Prediction System (TOPS) as described by Clancy (1981). Both prediction systems were conceived to provide routine operational numerical forecasts eventually out to two weeks. Today, in 1983, NOGAPS is producing forecasts out to five days and TOPS is running to 24 hours.

It can be seen that we are only at the early end of the two week forecast objective. At these short forecast times it is generally agreed that boundary effects, particularly time changing boundary effects, between the atmosphere and ocean play

less important roles than in the longer time scales. Thus, NOGAPS and TOPS have developed essentially independent of each other.

In recognition that NOGAPS forecasts beyond about three days may well need time varying boundary conditions at both its upper and lower boundaries, NEPRF sponsored a study of the state of the art of coupled forecast systems. The portion of that study, as documented by Elsberry et al. (1982), devoted to ocean interaction formed the basis of the workshop we are reviewing in this report.

1.3 Workshop Structure

The Workshop opened in Room 200 of Building 14 at the Naval Postgraduate School (NPS) Annex, Monterey, California at 0830 on August 30, 1982. The morning of August 30th was devoted to descriptions of the Navy atmospheric and ocean prediction systems. The afternoon, although starting with a review of the Elsberry et al. (1982) study, was largely taken by presentations by workshop attendees of relevant results. Section 2 of this report contains summaries of each of the August 30th afternoon presentations.

August 31st was devoted to discussion and synthesis of the previous day's material into a sequence of recommendations. During the morning these discussions took place in concurrent, physically separate, ocean and atmosphere modeling group meetings. In the afternoon the groups assembled together to exchange conclusions and recommendations. Appendix A is a copy of the full workshop agenda.

Workshop participants included knowledgeable academic and government scientists who are presently involved in either atmospheric or ocean modeling on 3-15 day time scales. It should be emphasized here that we purposefully excluded both small scale/short range and very large scale/climate research from consideration at this workshop in order to focus on the unique 3-15 day problems. Appendix B is a listing of workshop attendees.

1.4 Objectives

Often workshops of this nature have as their key objective a state of the art (or science, or technology) review. In this case that state of the art review was only a preliminary objective along the way toward action recommendations.

Clearly, before one can set a proper course of action, one must know present conditions. In that sense, the first objective of the workshop was to establish the current state of atmosphere and ocean prediction models. This review would then allow a reliable estimate to be made of the viability of coupled systems now or ever.

From the outset we realized that a fully coupled system was not imminent. Consequently, the most important objective of the workshop was to set a course of action that would eventually produce the best degree of ocean atmosphere coupling in an operational forecast system.

clusions and recommendations in the context of the three coupling scenarios that Elsberry et al. (1982) defined in their study of the problem. Those scenarios are labeled weak, nonsynchronous and synchronous coupling and are designated as scenarios A, B, and C, respectively, in that report.

1.5.1 Weak Coupling.

Weak coupling is simply the best possible specification of the interface boundary conditions (e.g., ocean sea-surface temperature, atmosphere winds) at the start of the forecast period. In this coupling mode, the boundary conditions are held constant throughout the forecast period. Once initialized with the same boundary conditions, the atmospheric and ocean models proceed through their separate forecasts independent of one another. In this mode the sequence of ocean and atmosphere model runs is of no importance in any operational job stream.

1.5.2 Non-Synchronous Coupling.

In nonsynchronous coupling, the model run sequence <u>is</u> important. This mode starts with weak coupling as defined above but only for one of the models. At the conclusion of that first model's forecast, it delivers a set of calculated time varying boundary conditions to the other model. Eventually, whenever the second model runs, it uses the time varying boundary conditions from the first, rather than the fixed conditions of weak coupling. Non-synchronous coupling as we have described it above is similar to what others have called "one-way interaction."

In one case, the ocean model would run first starting its forecast with the best possible atmospheric winds and heat flux at the start, holding these conditions constant through the forecast period and producing a set of time varying sea surface temperatures. The atmospheric model then would next run using these sea surface temperatures as time varying lower boundary conditions.

The opposite case of nonsynchronous coupling would have the atmospheric model run first with fixed SST conditions to produce time varying boundary layer winds and heat fluxes. The ocean model would then run with the time varying forecast winds and heat fluxes at its upper boundary.

1.5.3 Synchronous coupling

In synchronous coupling the models run in lock step with each other as happens in nature. In this mode, one model starts with the best possible analysis and runs for just a short time, thereby producing a short forecast of boundary conditions for the companion model to use for its first short forecast. This companion model then projects a short time into the future to deliver new boundary conditions to the first model. This alternating mode of short forecasts allows continuous feedback between models as occurs in nature. Some treatments of related problems have defined synchronous coupling as "two-way interaction."

It should be emphasized that synchronous coupling, although the most realistic, is also the most complicated of the three scenarios both for computation and for diagnoses if something is in error.

days and 15 days.

Three days is the shortest time period where coupled forecast need be considered altogether. NOGAPS presently runs out to approximately this time period. TOPS will shortly run to 3 days as well.

Seven days is a reasonable short term objective for both NOGAPS and TOPS without any major redevelopment of either model's physics and/or numerics. Fifteen days is the long range objective that is generally considered to be the limiting time scale for dynamic atmospheric prediction.

1.7 Conclusions and Recommendations

We present the detailed conclusions and recommendations of the assembled atmosphere and ocean modelers in Sections 3 and 4 of this report, respectively. Here we summarize those thoughts.

1.7.1 Atmospheric Models.

The real atmosphere responds in a highly nonlinear way to boundary layer forcing. Present generation atmospheric models have much of that nonlinearity. The boundary layer forcing may be due to topography, stratospheric forcing, latent heat release in clouds or the subject under consideration here, SST changes. The complicated interaction of all of these forcing functions led the atmospheric modelers to suggest caution in their conclusions and recommendations.

the conclusions were definitive. For three days, the conclusion was that weak coupling using a good SST analyses would improve the atmospheric forecast. A poor SST analyses, however, might do more harm than good. For 15 days, synchronous coupling was the only viable option.

For seven days, there was much less certainty. The expensive price to be paid for synchronous coupling had to be balanced against the loss in realigning of weak coupling (i.e., constant SST for a full seven day period). The only definitive conclusion here was that nonsynchronous coupling was not a viable middle ground option.

1.7.1.2 Recommendations. For 3 day atmospheric forecasts the group recommended implementation of weak coupling using the TOPS-EOTS analyses. The recommendation was strong in requiring the inclusion of satellite SST data and careful quality control on the SST analysis to ensure against climatological bias in data poor areas and diurnal changes.

For seven days, the group recommended cautious implementation of weak coupling, but with close monitoring of the effects. Here again, the SST analyses must be under strict quality control.

Eventually, synchronous coupling should be implemented for both 7 and 15 atmospheric forecasts. Before operational centers seriously consider synchronous coupling, however, there must be extensive case study experimentation to understand ocean-atmospheric interaction. The case studies should use state of the art research models that have detailed diagnostic elements. In

order to focus on the atmospheric response, the ocean boundary forcing should be provided by observed, rather than predicted time varying SST data. Without this careful approach, the highly nonlinear nature of atmospheric models will cause synchronous coupling to lead to chaos.

1.7.2 Ocean Models

Ocean response to atmospheric forcing on a time scale of 3-15 days is much more linear than is the reverse. Consequently, the conclusions and recommendations concern simpler ocean-atmosphere interactions from the ocean modeling standpoint than those from the atmospheric vantage point.

1.7.2.1 Conclusions. The evolution of the surface mixed layer (ML), the sea surface temperature (SST), and the seasonal thermocline has proven to be highly predictable with a variety of models, if the atmospheric forcing which drives the mixed layer is known accurately. Therefore, it is expected that the greatest improvements in upper-ocean prediction will be achieved by improving the surface fluxes produced by the atmospheric models. In this regard, the elimination of long-term bias in the net surface heat flux predicted by the atmospheric model is of maximum importance, since such a bias can lead to spurious ocean thermal anomalies in an ocean analysis/forecast system.

At the moment, no definitive studies have been completed which study the effect on mixed layer evolution of errors in the atmospheric forcing functions. Similarly, no definitive studies have been completed using coupled air-sea models for time scales of the order of 1-10 days. Thus we do not know at the present

(beyond some scale analysis) either the changes in atmospheric surface fluxes, or the corresponding changes in SST and ML, that would result from such coupling. The advantage or disadvantage of using a fully interactive, operational, air-sea prediction system remains speculative at this point.

The deep ocean, as well as phenomena in the upper ocean which are essentially hydrodynamical in nature (e.g., western boundary currents, rings, and eddies), respond only weakly, if at all, to fluctuations in winds and surface heat fluxes on time scales of 1-10 days. Therefore, a fully interactive air-sea coupling has little implication for this aspect of the ocean prediction problem.

1.7.2.2 Recommendations. Like the atmospheric models, the ocean modeling group recommended immediate implementation of weak coupling of NOGAPS and TOPS/EOTS. The recommendation went on to call for an operational evaluation of this coupling soon after its implementation.

The second major recommendation called for experimental evaluation by R&D activities of NOGAPS-TOPS/EOTS interaction in both synchronous and nonsynchronous modes. The group recommended approximately 3 simulations per month, with one of these being of seven days duration. Finally, the group recommended that the same initial conditions for these simulations be provided to several research groups for model intercomparison.

The final recommendation called for improved observations. These included: (a) heat flux and stress from satellites; (b) cloudiness; and (c) horizontal variability of the mixed layer/thermocline on scales of 100 km.

SECTION 2
WORKSHOP PRESENTATIONS

Following are written summaries of the presentations that were made by the workshop participants. We present them to give the reader a feeling for the basis of the conclusions and recommendations that are provided in Sections 3 and 4.

Navy Atmospheric Prediction Model

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The Navy Operational Global Atmospheric Prediction System (NOGAPS) has been operational at Fleet Numerical Oceanography Center (FNOC) since October 1981. The heart of the system is a 2.4^ox3.0^ox6 sigma layer version of the UCLA general circulation model (GCM). The model uses an energy and enstrophy conserving horizontal differencing scheme. Wind and mass variables are distributed horizontally with a scheme C staggering system (Fig. 1). Explicit leapfrog time differencing is used with a time step of 4 minutes.

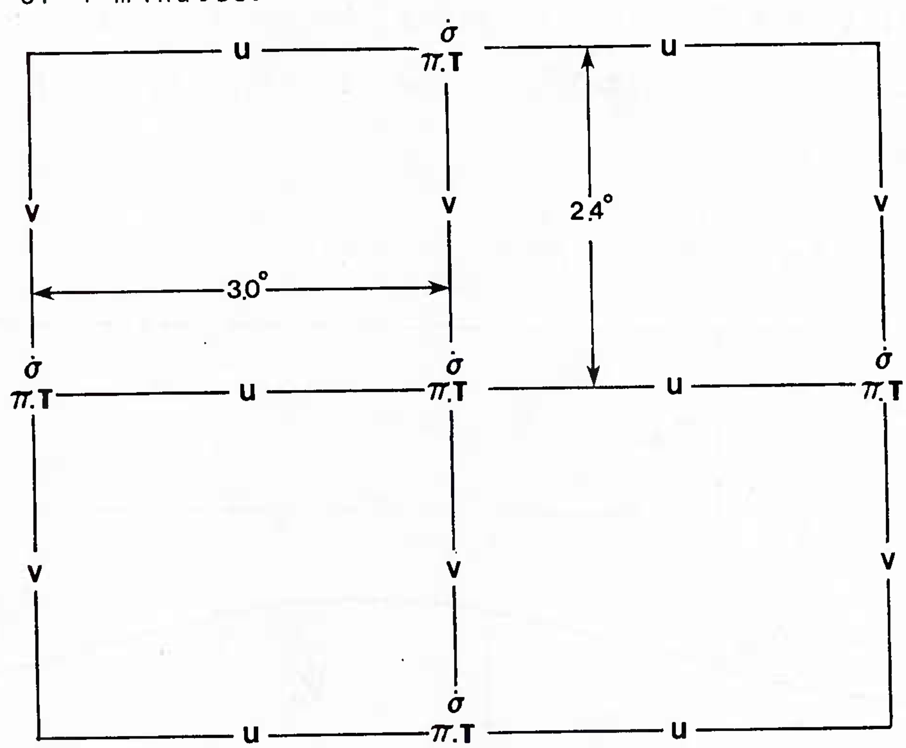

Figure 1

The diabatic processes in the NOGAPS model are of full GCM sophistication. The planetary boundary layer (PBL) is defined as a well mixed layer and is based on the formulation of Randall (1976) and Deardorff (1972). Radiation, both short and long wave, is formulated per Katayama (1972) and Schlesinger (1976). The Arakawa-Schubert (1974) cumulus parameterization is used for PBL based convection, moist convective adjustment for elevated instability. Large scale precipitation is computed for stable saturation; falling rain saturates layers below as it falls and evaporates. Ground temperature, ground wetness, snow and ice melting, and runoff are also predicted.

The PBL formulation in the NOGAPS model is of particular interest, as it is a unique feature of the model. The PBL is defined as a well mixed layer which exists in a somewhat "parasitic" mode with the sigma coordinate system and large scale variables of the model. A mean PBL property ψ_M (Fig. 2) is defined as

$$\psi_M = C_1 \Delta\psi + C_2 \psi_{LM} + C_3 \psi_{LMM1}$$

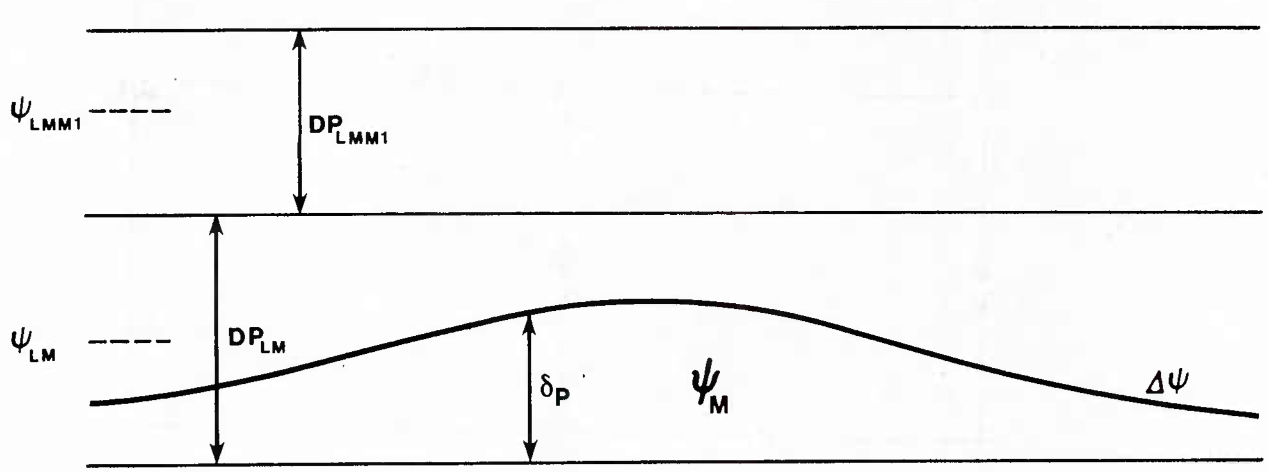

Figure 2

where C_1, C_2, C_3 are extrapolation coefficients and functions of δ_p, DP_{LM}, and DP_{LMM1}. ψ_{LM}, ψ_{LMM1}, and $\Delta\psi$ are prognostic variables. ψ can be U, V, T, or Q, the momentum, temperature or mixing ratio variables of the model. Prognostic equations are also carried for δ_p, ΔU, ΔV, ΔT, and ΔQ (see Randall, 1976). A constraint is placed on δ_p so that the PBL remains in the bottom sigma layer of the model. This imposes a maximum PBL depth of about 200 mb. The physical processes represented in the PBL are fluxes of heat, moisture, and momentum, entrainment across the capping inversion (from ΔT and ΔQ), cumulus cloud mass flux, and radiation from possible stratus occurring under the inversion. Surface fluxes are parameterized using the PBL stability, PBL depth, and surface roughness (Z_0) dependent drag coefficients of Deardorff (1972). Z_0 is constant over land and ice, and a quadratic function of wind speed over water.

NOGAPS is run operationally every 12 hours on 00Z and 12Z data. A six-hour cycle data assimilation cycle using the NOGAPS model is also run. The FNOC data base is accessed for all available data. This data consists of

Rawinsondes (mandatory and significant)

Pibals

Satellite retrieved temperatures

Aircraft winds and temperatures

Satellite cloud track winds

Ship reports

In addition FNOC operational analyses of

Sea level pressure

Sea surface temperature

Ice cover

are used.

NOGAPS currently runs on a Control Data CYBER 203 at FNOC. In the winter of 1983 the machine will be upgraded to a CYBER 205, at which time a nine-level version of NOGAPS should be implemented. Future plans include an increase in horizontal resolution, the extension of the forecast domain into the stratosphere (currently the model domain stops at 75 mb), and hopefully an interactive ocean mixed layer model. The last goal represents an area of extreme interest to the Navy, since the ocean atmosphere interface is the focal point of practically all Navy operations.

The Role of Air-Sea Feedback Coupling in Analysis and Prediction of Ocean Thermal Structure at FNOC

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An ocean thermal analysis/forecast system is functioning in real time at the U.S. Navy's Fleet Numerical Oceanography Center (FNOC), Monterey, California. This paper provides a brief description of the system and summarizes results illustrating its performance during the period 1 February through 1 June 1982. In addition, it gives a short discussion of the anticipated role of air-sea feedback coupling between the ocean analysis/forecast system and the atmospheric model that drives it. A comprehensive description of the system and thorough discussion of the results can be found in Clancy and Polak (1982).

The forecast component, designated as the Thermodynamic Ocean Prediction System (TOPS), is a synoptic mixed-layer model that employs the Mellor and Yamada (1974) Level-2 turbulence parameterization scheme and includes advection by instantaneous wind-drift and climatologically averaged geostrophic currents. During the period of study, TOPS is forced by surface fluxes predicted by the hemispheric meteorological forecast model of Kesel and Winningoff (1972). Effective 3 August 1982, however, the NOGAPS global atmospheric model (Rosmond, 1981) provides the forcing. In general, one 72 h TOPS forecast is performed each day.

The objective analysis component, designated as the TOPS-Expanded Ocean Thermal Structure (TOPS-EOTS) analysis, is a modified version of the conventional EOTS analysis (Holl et al., 1979), which was the Navy's official ocean thermal analysis product during the period in question. It uses information blending techniques to map XBT and surface ship observations daily to a three-dimensional Northern Hemisphere grid, also used by TOPS, which has roughly 300 km horizontal spacing in midlatitudes. It is coupled to TOPS in cyclical fashion, providing initial conditions, on any given day, for a 24 h TOPS forecast that is subsequently fed back into TOPS-EOTS as a first-guess field for the following day's analysis. This supplies additional information to the analysis by linking it to the atmospheric forcing via the physics of TOPS, and allows representation of upper-ocean variability on time scales too short to be resolved adequately by the ocean thermal observations.

Unlike those of the conventional EOTS analysis, day-to-day changes of the sea surface temperature (SST) field produced by the TOPS-EOTS analysis exhibit a low noise level and increase following the spring transition of the mixed layer. In addition, changes of the TOPS-EOTS thermal field tend to be consistent with the predictions of TOPS and, hence, the atmospheric forcing, while those of conventional EOTS do not.

Time series of net surface heat flux and mixed-layer depth (MLD), spatially averaged over regions of area (10^7 km^2), show that the spring transition of the mixed layer predicted by the TOPS/TOPS-EOTS system occurs in qualitative agreement with the atmospheric forcing. Although the spatial averaging tends to smooth temporal variability, the spatially averaged MLD still shallows fairly abruptly, indicating that the transition occurs almost at once over very large regions. Concomitant with the shallowing of the layer, the spatially averaged SST begins to increase rapidly.

The response of the model mixed layer to diurnal solar heating during the spring is also illustrated by time series of spatially averaged MLD and SST. In a relative sense, the mixed layer tends to be shallow and warm following the daytime heating and deep and cool following the nighttime cooling, as expected. Moreover, the capability of the system to represent variability on time scales too short to be resolved adequately by the ocean themal observations is demonstrated.

Composites of forecast verification statistics for the month of May indicate that TOPS exhibits skill consistently in forecasting the patterns of MLD and SST change, even for a forecast period (referred to as "TAU") of 72 h. Root-mean-square (RMS) forecast errors for MLD, again composited for May, show that TOPS betters persistence in all cases, except TAU=72 h for the Pacific test region. Similar RMS statistics for SST, however, indicate that TOPS betters persistence only at TAU=24 h for this parameter. This is a result of a warm bias in the net surface heat flux predicted by the FNOC atmospheric model.

In addition, the bias in the surface heat flux leads to spuriously warm surface temperatures in the TOPS-EOTS analysis by the end of May in high-latitude regions where the ocean thermal observations are too sparse to effectively update the model-predicted thermal field (i.e., Sea of Okhotsk, Bering Sea, Labrador Sea). Of relevance to this problem is the fact that the oceanic and atmospheric models are only one-way interactive during the study period. That is, the atmospheric model provides the forcing for TOPS, but the TOPS/TOPS-EOTS SST is <u>not</u> fed back to the atmospheric model as a lower boundary condition for the heat flux calculations. Instead, the SST used by the atmospheric model is provided by the conventional EOTS analysis, which essentially represents climatology in data-void areas. Thus, there is no mechanism for the oceanic consequence of bias in the surface heat flux to influence the atmospheric model.

In a two-way interactive system, however, the strong <u>negative</u> feedback between the downward surface heat flux and SST, combined with the constraints placed on the atmospheric model by the meteorological observations upstream and downstream from a data-void ocean area, will tend to reduce the biases in the net surface heat flux and suppress the formation of spurious ocean thermal anomalies. Consequently, a two-way interactive coupling between TOPS and NOGAPS, similar to the "weak coupling" case advanced by Elsberry <u>et al</u>. (1982), but with the ocean model used in forecast mode rather than hindcast mode, is advocated.

World Ocean Model
A Preliminary Report

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The primary objective of the World Ocean Model (WOM) development project at NORDA is to provide the Navy with a Global Ocean Prediction capability. The general approach presently being pursued to achieve this goal is to couple low vertical resolution, eddy resolving horizontal resolution hydro/thermodynamic general circulation models with embedded, high vertical resolution, one-dimensional, mixed layer models (e.g., TOPS).

The eddy resolving general circulation models would be used to predict the large/mesoscale current and temperature fields. These fields then would be used to provide the advective fields in the embedded mixed layer models. The mixed layer model would in turn be used to derive the detailed upper ocean current and temperature structure. This coupled system would also be used to provide a dynamical basis for ocean data analysis in data sparse areas (i.e., in a 4-D Data Assimilation mode).

A major obstruction to achieving this goal is that the present computer resources do not allow a global model with sufficient horizontal resolution to be run efficiently. For the model to run efficiently it must be totally contained within the central memory of the CYBER 205. The CPU time overhead required by paging in the virtual memory system is prohibitively high for efficient operation. For example a one-active layer, reduced gravity, hydrodynamic version on a 3/8 x 1/4 degree grid with a 1/2 hr time step and a REAL*4 capability would require 2.5 min for a 3 day forecast if the model was core contained and 6 hrs if page faulting was required.

Therefore an alternative solution must be found, such as developing smaller scale basin size models which are able to remain core contained. However, this approach is not without problems in that it introduces the nontrivial problem of open boundaries. It is well known that the specification of open boundary conditions in conjunction with the oceanic primitive equations system is an ill-posed mathematical problem and that an improper specification can lead to serious complications. To reduce the severity of this problem, the large scale global model will be used to provide boundary and initial conditions for the basin models and thus supply a dynamical constraint on the open boundaries.

Experiments have been performed using the one-active layer, reduced gravity, hydrodynamic version to test the effects of adding irregular coastline geometry to the model while forcing the model with a simple analytic wind function. First the model was run without any continents. The results showed strong easterly flow around the equator and strong westerly flow near the poles in direct response to the wind forcing. The inclusion of "block" continents (all continental boundaries were north/south or east/west) resulted in the formation of gyres in the major basin with westward intensification and a strong circumpolar current near the southern pole. Finally the inclusion of a detailed coastline geometry (based on digitized data) resulted in more realistic large scale currents, in particular the western boundary currents.

Experiments with the two-active layer version are presently being conducted to test the addition of a linear stratification in the second layer (i.e., to simulate the main thermocline). Also a surface wind climatology is being constructed from the MNC Global Analysis data set. This wind climatology will be used in future experiments and to eventually spin-up the first operational version.

Thoughts to Coupled Ocean-Atmosphere Models

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Assumptions

1. The large-scale, seasonal evolution of the atmospheric circulation is determined by the horizontal (north-south and east-west) distribution of heat/moisture sources over land and the sea.

2. The short-term response of the atmosphere to a region with higher sea-surface temperature is an enhanced upward surface heat flux.

   a. In the mid-latitudes, the enhanced surface heat flux is primarily redistributed locally by the quasi-horizontal circulation in the extratropical cyclone circulation.

   b. Because of the vertical gradient of moist static energy in the tropics, an enhanced surface heat/moisture flux is redistributed vertically over deep layers.

      1) There is a local or mesoscale response to the release of latent heat in the deep convection areas.

      2) There is also a large-scale response in other parts of the tropics (east-west) as well as a forcing of the long waves in the mid-latitudes (Horel and Wallace, 1981; Webster, 1981; Hoskins and Karoly, 1981).

3. On diurnal and synoptic time scales, the sea-surface temperature in the open ocean responds directly to the imposed atmospheric forcing.

a. Significant decreases in sea-surface temperature occur in regions of enhanced wind speeds and upward heat flux (i.e., during the passage of storms).

b. In regions of low winds and net downward heat flux, the solar radiation that is absorbed very close to the surface is retained in a shallow layer, and the sea-surface temperature increases rapidly.

1) In mid-latitudes, the increase in sea-surface temperature primarily occurs between storm passages, so that the increases do not persist and accumulate.

2) In the subtropic and tropics, the solar fluxes are large and periods of weak winds are often persistent, so that significant sea-surface temperature increases may be sustained.

Hypotheses

1. The prediction of sea-surface temperature changes on diurnal and on synoptic time scales in the tropics and subtropics will contain significant errors.

   a. The shallowing of the ocean mixed layer (and the subsequent increase in sea-surface temperature) is a delicate balance between the cube of the surface wind speed and the magnitude of the downward heat flux.

   b. The primary determinant of the solar flux is the amount of cloud cover, which has low predictability because of space/time scales involved and inadequate process parameterizations.

   c. In the Mellor-Durbin type models, the entrainment mixing is extremely sensitive to the phase relation between the vector wind stress and the model-simulated (vector) currents. As the winds are varying on the atmospheric synoptic scale while the ocean currents have a large amplitude on the inertial time scale, it is very likely that the predicted entrainment mixing (ocean cooling) events will frequently have an incorrect phase.

2. Synchronous coupling of an oceanic prediction model to the NOGAPS model will add an additional degree of freedom that is likely to reduce atmospheric predictability.

a. If the atmospheric model latent heat parameterization scheme is very sensitive to the sea-surface temperature distribution between cloud-free and cloudy regions, erroneous deep convection will result that will have a detrimental effect on the prediction both of local and of remote atmospheric circulations.

b. If the parameterization scheme is relatively insensitive to the sea-surface temperature distribution, the negative feedback loop that exists in nature will not be well predicted, and excessive boundary layer energy will be accumulated for eventual release at an incorrect location and time.

3. Because of the dominant role of cloudiness in specifying the surface heat sources (over land as well), there is no assurance that a coupled atmosphere-ocean model will attain the correct equilibrium state on time scales of 5-10 days. The accumulation of errors in the ocean model, especially in regions without adequate oceanic observations for correcting the solution, may cause continuing problems in the representation of the large-scale atmospheric circulations on monthly/seasonal time scales.

Ocean Thermal Response to a Global Sector Atmospheric Numerical Model

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The Garwood (1977) bulk, oceanic mixed layer model is used to simulate the short-term response in a 60^0 global sector. The atmospheric forcing is derived from a version of the UCLA general circulation model used by Sandgathe (1981) to study the role of air-sea fluxes in maritime cyclogenesis. A five-day integration of the ocean model is made using the complete 3 h momentum and heat fluxes calculated by the sophisticated planetary boundary, latent heat and radiative parameterizations of the UCLA model.

The zonal mean sea surface temperature changes during the five days include increases of 0.4oC/day in equatorial regions and decreases of 0.2oC/day along the Northern Hemisphere storm track. Ocean temperature changes and the associated atmospheric forcing are related using a storm-following coordinate system. In addition to the general rapid warming of the ocean surface layers in the tropical regions, there is a large horizontal variability. High surface temperatures are produced during the periods of maximum insolation in the regions of light winds and low cloudiness. Considerable horizontal gradients in the sea surface temperatures are predicted between the cloudy and cloud-free regions. When daily-averaged heat fluxes are used to force the ocean model, the horizontal variations in mixed layer temperature and depth are more realistic.

These results have implications for coupling atmosphere and ocean models for short-term forecasting. Although the mid-latitude ocean response appears realistic, the ocean model is very sensitive to large horizontal variations in solar flux that are predicted between tropical cloud cluster and adjacent cloud-free areas. Such high sea-surface temperature gradients might be expected to lead to very vigorous deep convection in a coupled atmospheric model. Thus a fully synchronous coupled atmosphere-ocean model seems ill-advised. Both the atmospheric forcing provided to the ocean model and the sea-surface temperature provided the atmospheric model may have to be averaged in time and space.

Use of Satellite Derived SSTs in NWP

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This note is intended to point out two research and development activities which I feel in the immediate future (3-5 yrs) will be most beneficial to the Navy's NWP effort to extend the time range of useful atmospheric predictions. These activities can be viewed as alternatives to the development of a fully coupled and syncronous ocean-atmosphere prediction model.

1. Identify and correct the mean climate drift of the NOGAPS model.

An important deficiency often noted in atmospheric prediction models is that its mean climate, when run as a climate model, does not agree with the observed mean climate. Since the mean relaxation time of atmospheric climate perturbations is only a few days (Leith, 1975), the climate mean drift can produce significant biases in predictions. If these biases can be identified in the NOGAPS 72-120 hr forecasts (say), it may be that they can be easily corrected, either by improved process parameterizations or by simple empirical techniques.

2. Adopt low-pass filtered satellite SST's at the lower boundary.

Atmospheric prediction models have been shown to be very sensitive to the quality of the tropical data that is used to define the initial state (Somerville, 1980). Poor initial conditions in the tropics affect the ultralong waves during the first few days of the forecast period, resulting in a poor forecast (Baumhefner and Downey, 1978; Lambert and Merilees, 1978). It is reasonable to expect that the models are equally sensitive to the large scale heating pattern in the tropics which are determined to <u>some</u> extent by the oceanic surface temperatures (SST). The recent operational implementation of multi-channel techniques for calculating SST has substantially improved the reliability of the satellite derived SST fields (McClain, 1981; McClain <u>et al</u>., 1982; Pichel and Banks, 1982). The use of low pass filtered (10 days to reduce error noise) fields of satellite derived SST over the globe can be expected to improve the atmospheric model's ability to develop and maintain realistic large scale heat sources and sinks over an extended forecast period of 5-10 days.

Speculations on the Impact of Improved Air-Sea Exchanges in Storm Development in Operational Prediction Models

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Speculations in regard to impact of introduction of new complexities into ocean-atmosphere prediction systems can take a number of optimistic or pessimistic paths which appeal logically. Historically, many examples come to mind where pessimism preceded the introduction of enhanced prediction systems. In rough chronological order some of these include:

1. the barotropic atmospheric model
2. latent-heating addition to baroclinic models
3. dynamical hurricane prediction
4. global domains for short and medium range prediction
5. nonsmooth mountain profiles

to name a few.

On the other hand, arguments are made in the SASC report (Elsberry et al., 1982) for this meeting that too many degrees of freedom in an error prone system will degrade a coupled ocean-atmosphere system. This indeed is a possibility which must be explored.

From an operational point of view, a simplistic form of the coupling question can be phrased as follows:

Are errors produced by:

1. poor initial conditions
2. poor boundary layer parameterization
3. other model approximations likely to overwhelm any added information that might be gained by correctly changing sea surface influences during numerical integration of the atmospheric primitive equations.

One might answer this question with certainty under some circumstances, i.e.,

1. in sparse data regions
2. when sea surface exchanges are small and
3. errors in the system are more than likely to dominate ocean coupled features at later times in the forecasts.

This leaves open for consideration primarily extreme weather conditions near continental areas over short forecast ranges as situations where there are potential payoffs in coupled ocean-atmosphere models.

Some perspective on this type of forecast problem, was gained through experiments with NMC's LFM model applied to an east-coast winter storm that was strongly influenced by air-sea interactions.

This snow storm, the so called President's day storm, has attracted wide attention because of the devastating effect it produced in the Middle Atlantic States. The potential for a major storm was recognized before the fact based on synoptic experience and numerical guidance. A surface low was developing along a front stretching eastward out of the Gulf of Mexico. A cold blast of Arctic air was rapidly gaining low level moisture and sensible heat as it settled over the ocean southeast of the New England states. A middle tropospheric disturbance was moving from the northwest toward the east coast.

All these ingredients were undoubtedly factors in the development of the storm. But even in hindsight scientists disagree on the relative importance of all the ingredients or what specific errors resulted in an operational underestimate of storm development.

A warm active ocean that provided more energy for the cumulus clouds driving the CISK and enhancing baroclinic deepening processes was shown to be a significant feature in improving the forecast. More careful studies must be performed to determine whether a subtle or three degree change that might be offered by an active ocean model would be a significant influence in gaining the finest details of storm intensification.

Interactive Ocean-Atmosphere Modeling at the National Center for Atmospheric Research

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Interactive ocean and atmospheric models are being developed at NCAR for climate studies, since it is well known that important interactions between the ocean and the atmosphere exist on time scales of a month and longer. The basic framework for these studies is the Community Climate Model (CCM) which is a global, spectral model developed at NCAR for use by NCAR and university scientists for climate and forecast studies. This atmospheric model is being coupled to a hierarchy of ocean models, ranging from a simple energy balance (swamp) model to eventually a fully three-dimensional ocean model. Current research with the CCM involving ocean interactions include studies of the effect of increasing CO_2 on climate. This work, under the direction of W. Washington, is currently using the energy balance model and a mixed layer ocean model.

Another study involving interacting ocean-atmosphere models is being conducted by B. Semtner. In this intermediate climate model, a low-resolution, primitive equation atmospheric model developed by Held and Suarez is coupled to a mixed-layer ocean model developed by Kim and Heald. This ocean model gives a reasonably accurate prediction of sea-surface temperature over a two-year period when forced by observed atmospheric data.

Coupled ocean-atmosphere models are not being used for forecast studies at NCAR. However, studies of explosive marine cyclogenesis by Anthes and others have indicated strong sensitivity to the static stability in the lower 200 mb of the atmosphere. Proper determination of this static stability and the closely related sea-surface temperature is therefore important in short and medium range forecasts. It is probably necessary to have enough model layers near the surface to resolve the atmospheric structure in some of the cases of rapid cyclogenesis. However, it is unlikely, in my opinion, that a coupled ocean-atmosphere model would improve forecasts of these events on time scales of 0-10 days. This is because changes in sea-surface temperature over these time scales is not likely to exceed several degrees celsius, and the atmospheric model are generally not sensitive to changes of this magnitude. A more likely way to improve forecasts would be to improve the sea-surface temperature analysis.

In summary, forecasts of from 0-10 days are sensitive to the sea-surface temperature analysis, and improved forecasts would likely result from improved SST analyses. However, the models are not very sensitive to changes of SST of the order of 1oC on these time scales. Thus, even if an ocean model can predict such changes accurately, the feedback to the atmospheric model in a coupled system is likely to be minimal.

GLAS Activities in Atmospheric-Ocean Prediction

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The models that have been used in coupled ocean-atmosphere experiments are: 1) The GLAS climate model (Shukla et al., 1981) which is a 4° lat, 5° long and 9 uniform vertical levels model. It has a bulk parameterization of surface fluxes, diurnal cycle, interactive cloud-radiation, supersaturation and convective clouds. The finite differences is based on an Arakawa (1972) scheme B; 2) The GLAS 4th order global model (Kalnay-Rivas et al., 1977) - this model has the same physics but full 4th order horizontal finite differences. This model has been used with 4°x5° and 2.5°x3° horizontal resolution and 9 uniform vertical levels; 3) The GLAS upper ocean model (Schopf and Cane, 1982) which consists of two layers in the vertical governed by primitive equation dynamics lying on top of a quiescent abyss. The surface layer properties are also governed by slab mixed layer physics (Kraus and Turner, 1967); 4) A mixed layer ocean model (Schopf and Cane, 1982).

Other systems relevant to this research are 1) the GLAS analysis/forecast system (Halem et al., 1982; Baker, 1982) which has been extensively used for FGGE satellite weather impact studies; and 2) the GLAS temperature sounding system which, through the inversion of the radiative transfer equation, provides SST. For FGGE SOP-1, and over the North Atlantic and

Pacific, these SST's are within an rms difference of .7oK with the Navy SST analysis.

The experiments in progress at GLAS reported at the workshop were the following:

a) SST monthly mean predictability. The motivation of this study is the question whether for atmospheric dynamic predictions of monthly means one should use an interactive ocean model or SST's prescribed from the initial anomalies. The mixed layer model has been driven with 25 years of monthly averaged wind stress and heat flux data over the Atlantic (Bunker), and climatological initial conditions. The results indicate that the one month SST predictions have larger errors than decayed persistence. This may be due to the lack of horizontal advection as well as to the use of monthly average fluxes. Studies of the sensitivity to initial conditions and forcing errors are being conducted.

b) A one-way coupling of the GLAS atmospheric analysis during 2 weeks of FGGE SOP-1 forcing the upper ocean model. The ocean model was initialized with the GLAS retrieved SST, climatological mixed layer depths and zero currents. The results indicate reasonable changes in SST except near the continental boundaries, where the lack o;f currents produces rather large errors of the order of 3-5o in one week. We are presently studying how to best initialize the ocean currents. We plan to use geostrophic adjustment for the baroclinic currents and fixed barotropic currents.

c) <u>A 5-day atmospheric integration to determine the sensitivity to SST changes</u>. A first experiment showed very small changes (order of 4-8 mb in SLP) when the January 1979 SST was used instead of climatology. However, the impact may be situation dependent, and more cases will be run.

We plan to develop a high resolution version of the ocean model and perform fully coupled 2-week runs for situations in which a large impact may be expected, such as sudden deepening of the mixed layer due to the passage of a storm in the fall season.

Results of the Oregon State University Interactive Ocean-Atmospheric Model

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Review of an ocean-atmosphere coupled model developed at the Oregon State University (OSU) is presented. The primary purpose of developing such a model was to obtain climate simulation experience. It is conceivable, however, that coupled models may also be appropriate for use in long-range atmospheric forecast. The following discussion focuses on this particular subject based on an ocean-atmosphere coupled experiment.

The OSU coupled model utilizes the existing OSU 2-level atmospheric model (Schlesinger and Gates, 1981) and the OSU 6-level world ocean model (Han and Gates, 1982). Both models are based on the primitive system of equations and obtain solutions numerically on a 4° lat. x 5° long. horizontal grid mesh which covers the entire globe. Before carrying out the coupled experiment, each component model was tested in a series of extended control integrations in which the other component of the system was prescribed from the observed climatology. The results of these control experiments are presented first to illustrate the degree of model realism. A comparison between the simulated January mean sea-surface temperature (SST) and the observation shows a remarkable model accuracy over most of the world ocean (see Fig. 1). The major model discrepancies occur only in the

western boundary regions, equatorial oceans, and the eastern boundary regions. These errors are, however, by no means insignificant in view of important actual air-sea interactions taking place in these regions. The January mean surface heat flux and wind stress curl simulated by the atmospheric model are also compared with the observed estimates (see Figs. 2 and 3). Overall agreements are rather good, but over the North Atlantic and Pacific Oceans the simulated maximum surface heat fluxes are overestimated by almost 100 W/m^2, and the wind stress curl fields are poorly simulated. At present, the cause of these errors is not known. Yet these errors appear to be the major obstacles to be overcome in order to prevent the model from drifting to a spurious climate.

In spite of the known model deficiencies described above, there is a significant scientific as well as practical interest in pursuing ocean-atmosphere coupling experiments. First, by actually coupling the two models we obtain practical modeling experience. Also, some meaningful scientific inquiry may be made regarding the existing hypothesis on the large-scale ocean-atmosphere interactions, if they turn out to be not too sensitive to the model deficiencies. The following preliminary results of the 16 month integration of the coupled model are briefly discussed in the hope that they can shed some light on the stated objectives.

The ocean and atmospheric models were initialized using the data taken from the control experiments and were synchronously coupled during the entire period of integration. The January SST simulated for "year 3" shows considerable warming in the high latitude oceans and cooling in the middle latitude oceans (Fig. 4). Perhaps the most interesting SST changes occurred in the tropical oceans. A large area of warm SST anomaly in the eastern tropical oceans and a cold anomaly in the western tropical Pacific and Indian Oceans are particularly notable. A comparison between the SST and precipitation anomalies relative to the control case (Fig. 5) shows a positive correlation over the eastern tropical oceans, indicating general enhancement of cumulus convection due to the warm SST anomalies. No such local correlation, however, can be found over the western tropical Pacific and Indian oceans. In fact, a large positive rainfall anomaly is seen over the region of negative SST anomaly. Obviously the local influence of the SST anomaly on precipitation in this region is easily obscured by other dynamical effects such as the monsoon. Nevertheless, the large precipitation anomalies, presumably associated with the SST anomalies in the eastern tropical oceans, might have remotely influenced the middle latitude circulations in the Northern Hemisphere. Indeed, the simulated 400 mb geopotential height anomaly patterns (Fig. 6) relative to the control case are not inconsistent with the existing remote control mechanism of Hoskins and Karoly (1981).

Although the discussions above need to be further substantiated by more detailed analysis of the experimental results, they may lead to the following comments as regards the use of a coupled model for the long-range atmospheric forecast:

1) Extended integration of a global ocean-atmosphere interactive model is technically feasible and requires only moderate computer resources.

2) The major obstacle for the long-range forecast appears to be the model tendency to drift to a spurious model climate.

3) Actual forecast, as well as climate experiments, with coupled models and subsequent diagnosis of the experimental results may yield important clues for the necessary model improvements.

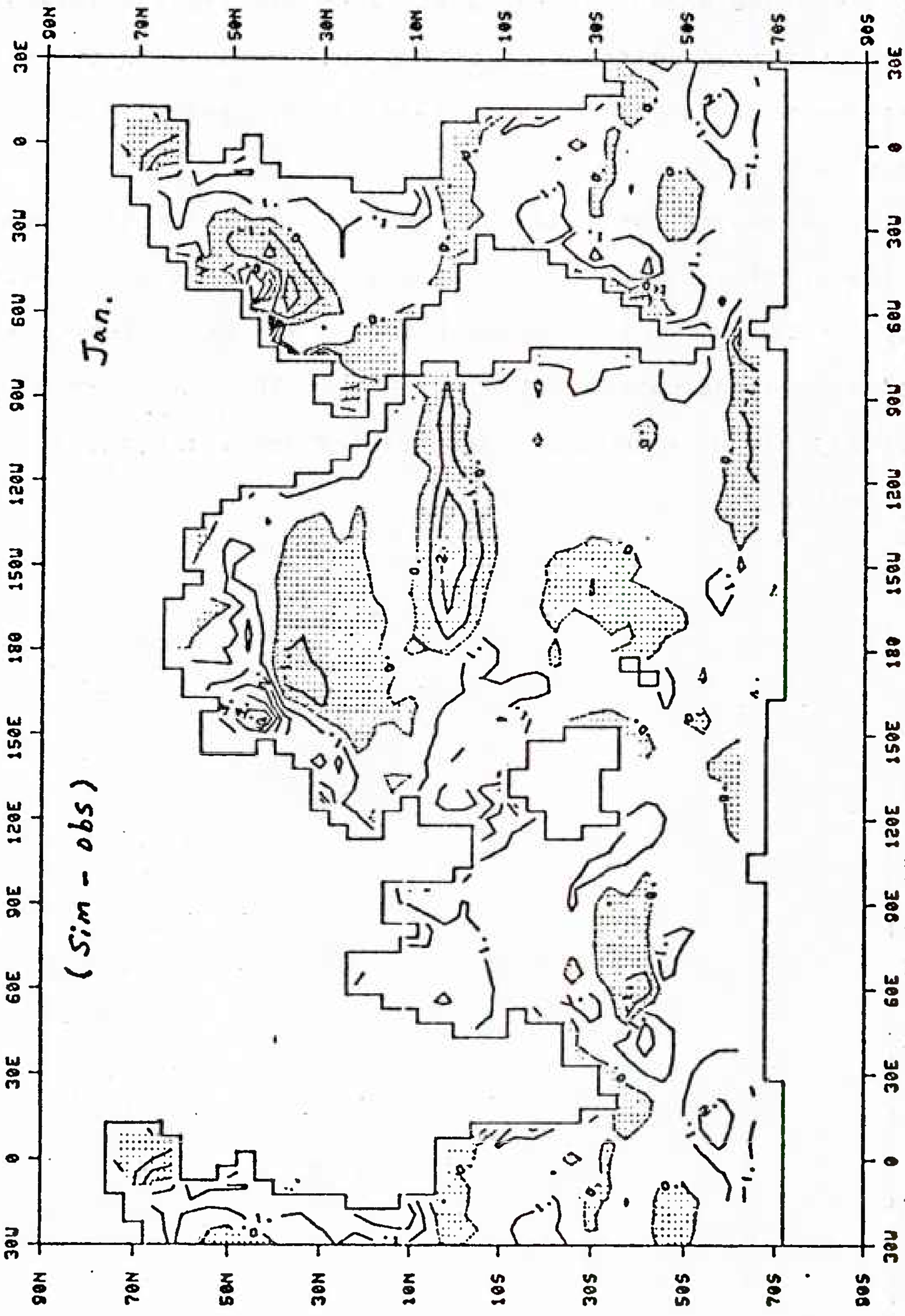
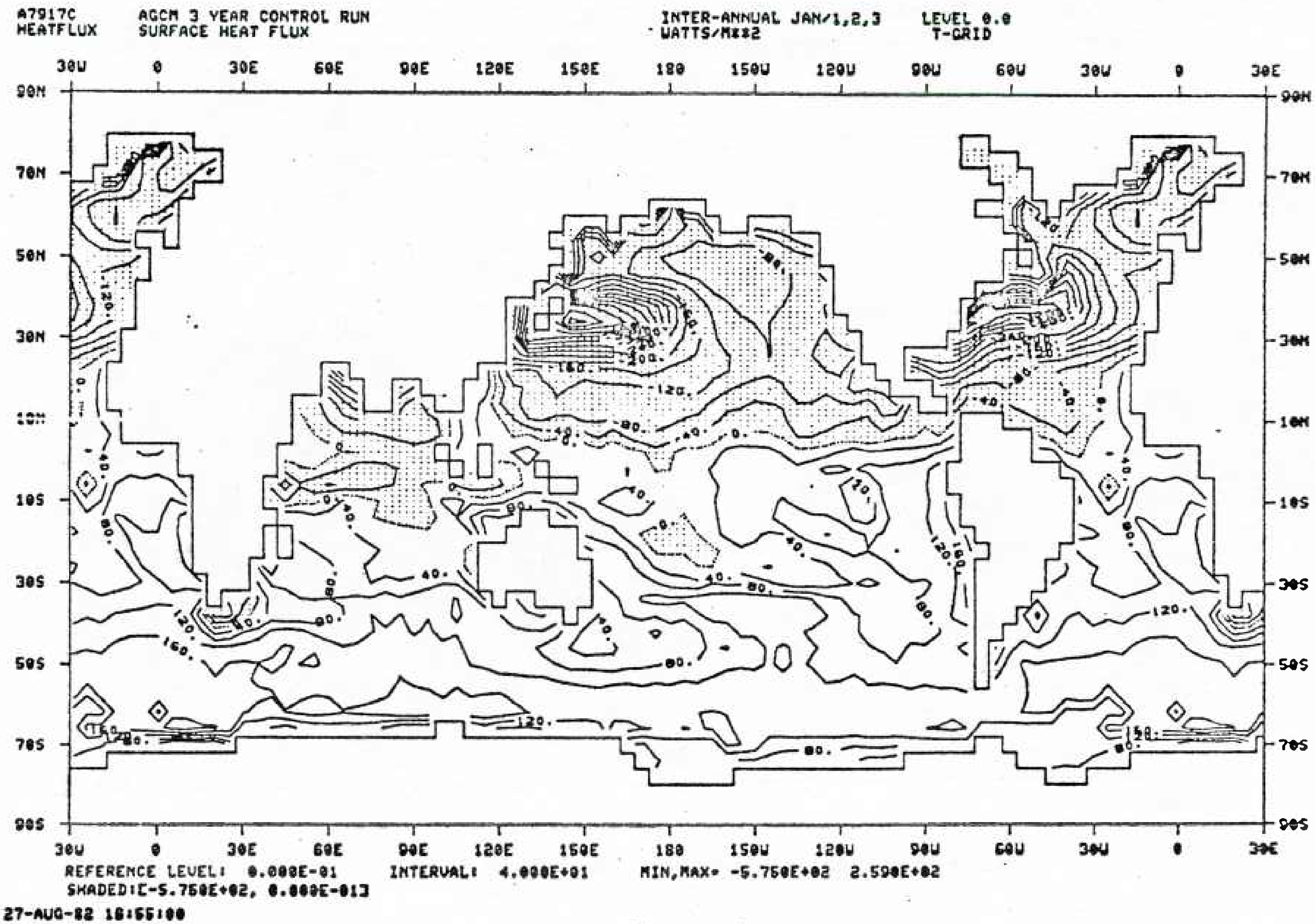


Figure 1.


A7917C
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AGCM 3 YEAR CONTROL RUN
SURFACE HEAT FLUX
INTER-ANNUAL JAN/1,2,3
WATTS/M**2
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T-GRID
30W 0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0 30E
90N 70N 50N 30N 10N 10S 30S 50S 70S 90S
REFERENCE LEVEL: 0.000E-01
INTERVAL: 4.000E+01
MIN,MAX= -5.750E+02 2.590E+02
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Figure 2a.

January mean net downward heat flux ($W\ m^{-2}$)

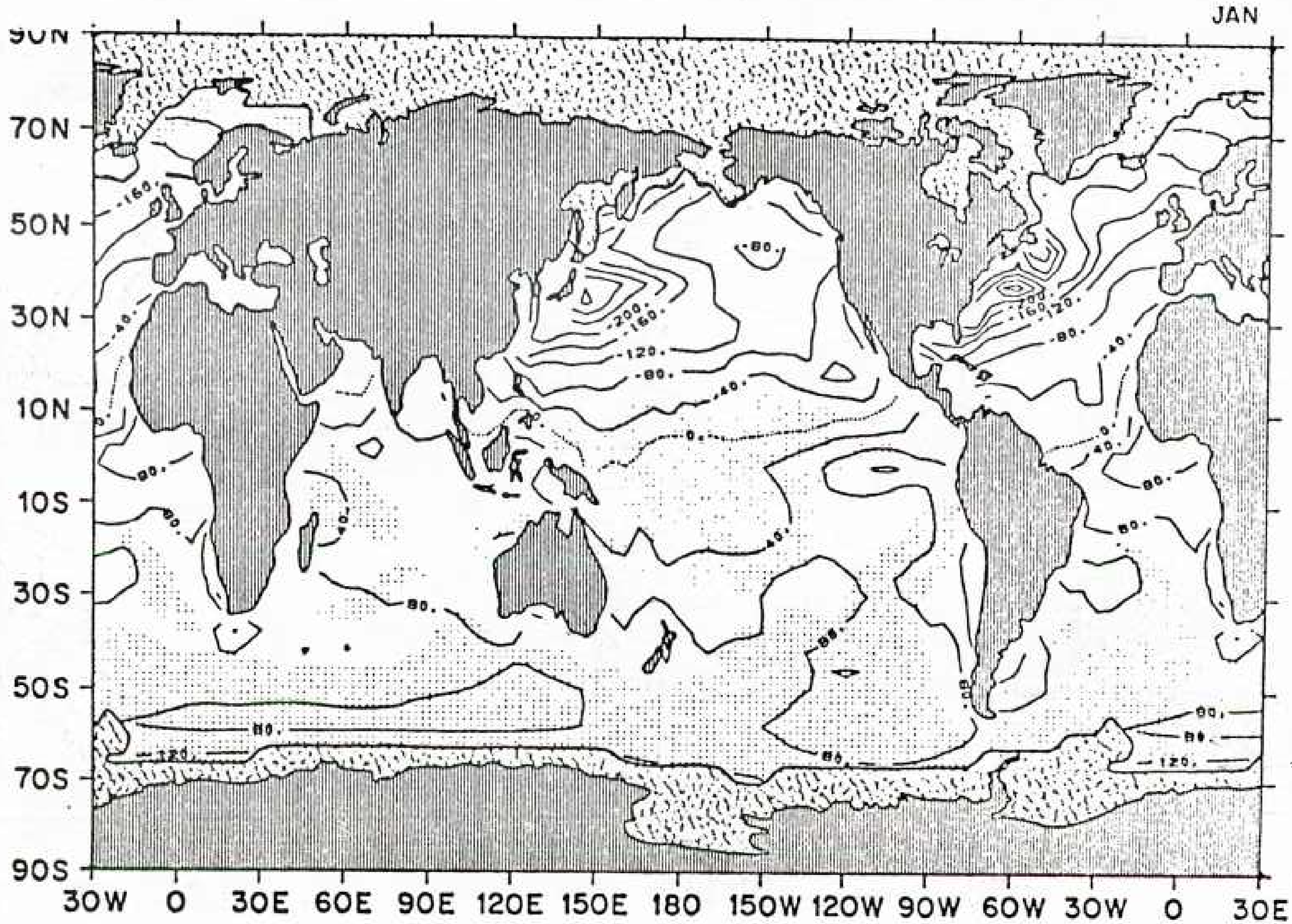
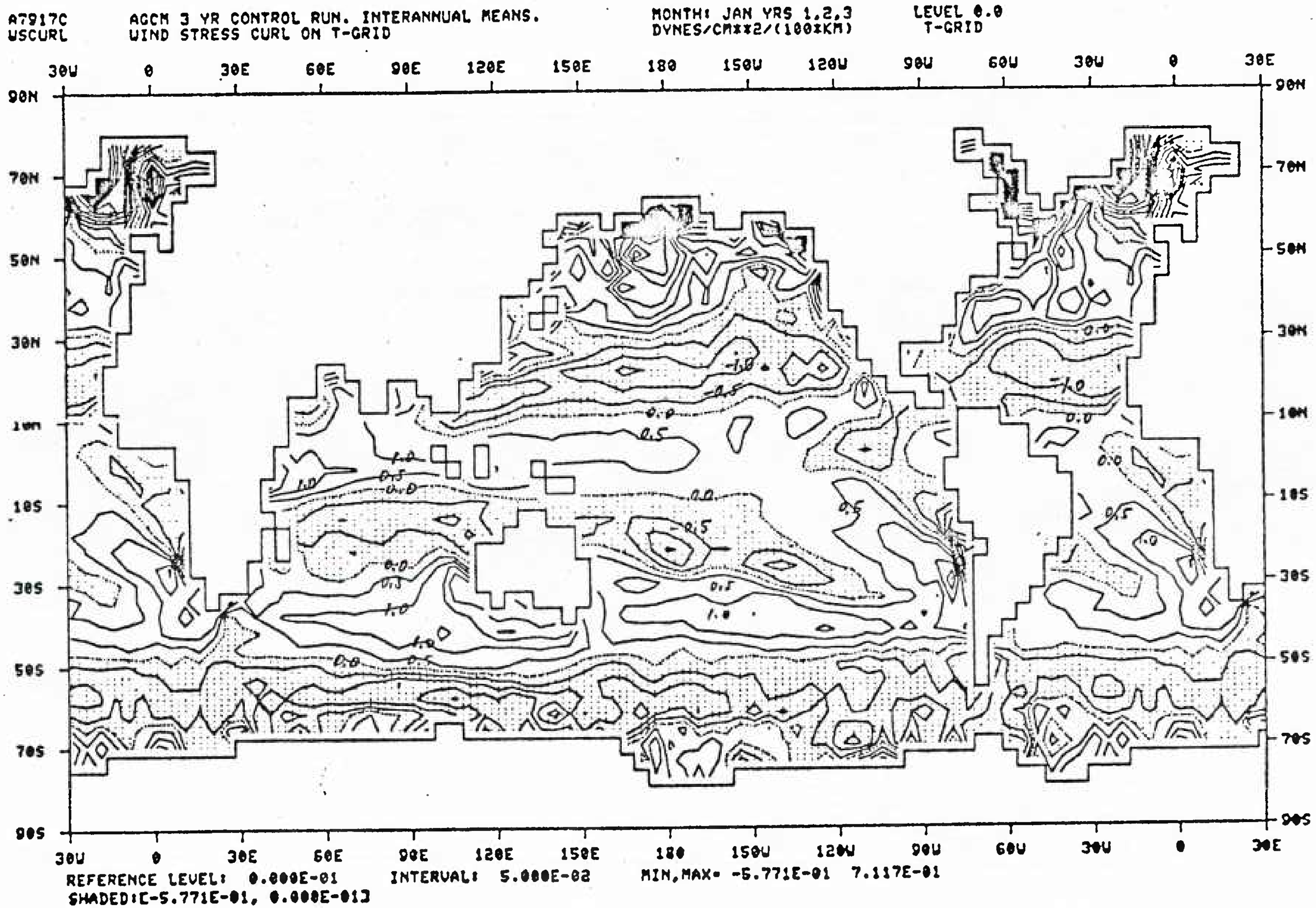


Figure 2b.


A7917C
USCURL
AGCM 3 YR CONTROL RUN. INTERANNUAL MEANS.
WIND STRESS CURL ON T-GRID
MONTH: JAN YRS 1,2,3
DYNES/CM**2/(100*KM)
LEVEL 0.0
T-GRID
30W 0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0 30E
90N 70N 50N 30N 10N 10S 30S 50S 70S 90S
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MIN,MAX= -5.771E-01 7.117E-01

Figure 3a.

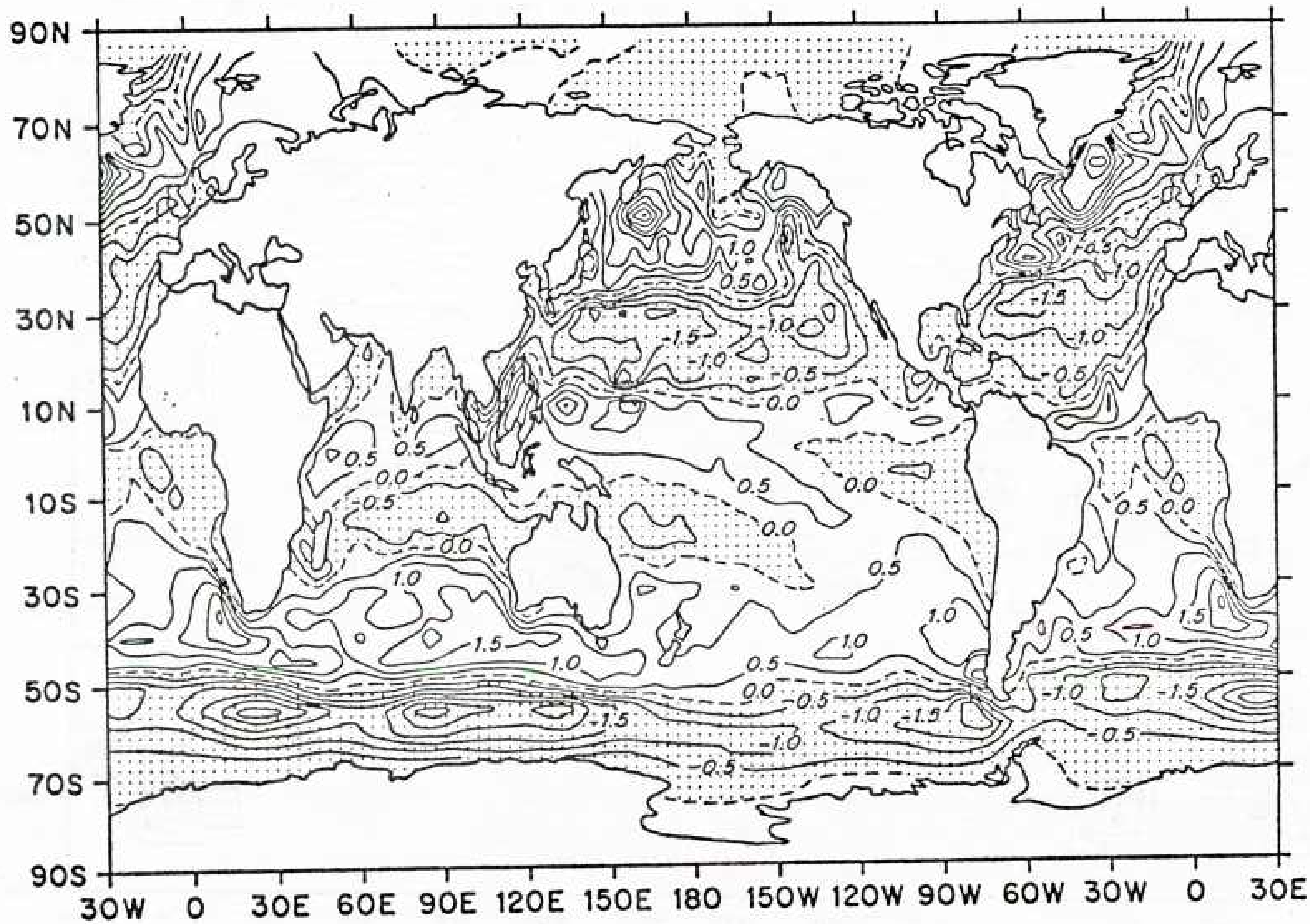
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E

Figure 3b.

CGCM82A1 COUPLED AGCM OGCM MINUS CONTROL 06/17/82 23:25:46

SST WATER PI SEA SURFACE TEMPERATURE DEG C

MEAN	N.MEAN	S.MEAN	MIN	MAX	JAN/ 3
0.38922	-0.29458	0.87023	-5.3961	8.7685	

MONTHLY MEANS 6.00 HR SAMPLE

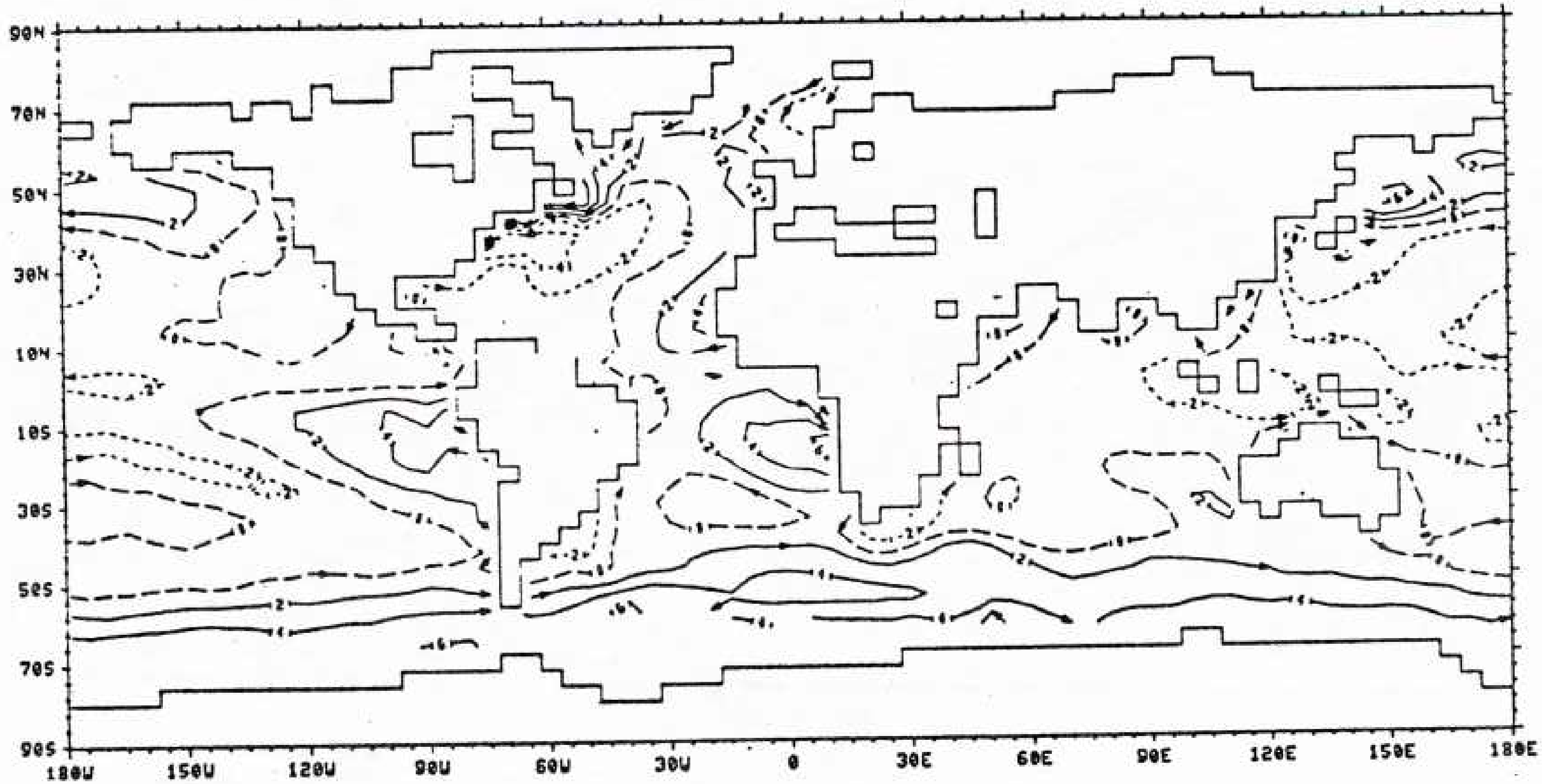

Figure 4.

23-JUN-82 09:14:19

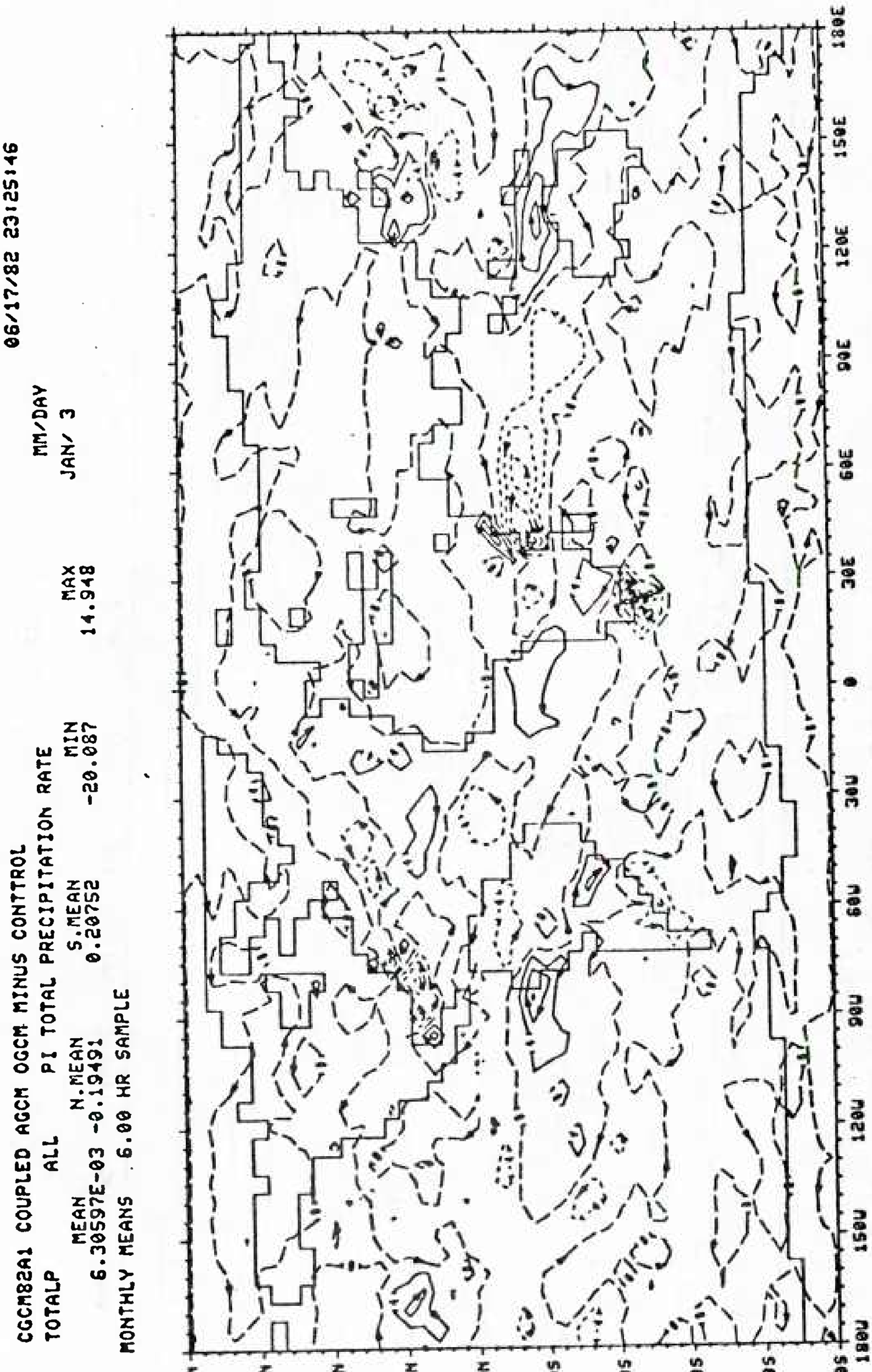
CGCM82A1 COUPLED AGCM OGCM MINUS CONTTROL
06/17/82 23:25:46
TOTALP ALL PI TOTAL PRECIPITATION RATE
MM/DAY
JAN/ 3
MEAN N.MEAN S.MEAN MIN MAX
6.30597E-03 -0.19491 0.20752 -20.087 14.948
MONTHLY MEANS 6.00 HR SAMPLE
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
180W
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180E

Figure 5.

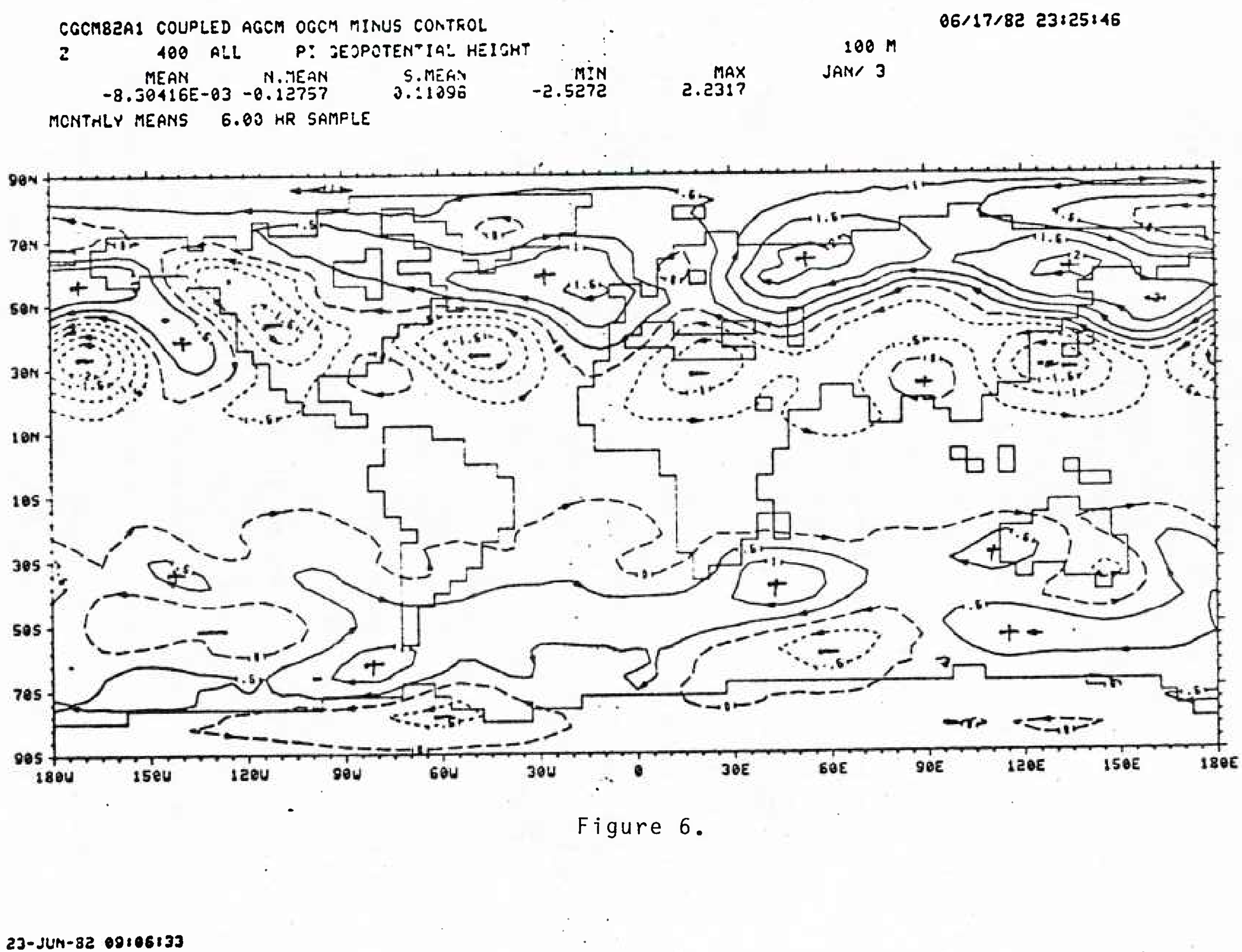
CGCM82A1 COUPLED AGCM OGCM MINUS CONTROL
06/17/82 23:25:46
Z 400 ALL P: GEOPOTENTIAL HEIGHT
100 M
MEAN -8.30416E-03
N.MEAN -0.12757
S.MEAN 0.11096
MIN -2.5272
MAX 2.2317
JAN/ 3
MONTHLY MEANS 6.00 HR SAMPLE
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
180W
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180E
23-JUN-82 09:06:33

Figure 6.

Predictability of the Ocean Mixed Layer

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Fundamentally, the roles of the oceans and atmosphere in the terrestrial heat circulation system are inextricably linked and it is artificial to draw any boundary, whether at the sea surface or the base of the ocean mixed layer, across which interactions are held to take place in one direction only.

On average the mixed layer transmits heat from the atmosphere to the deep ocean at low latitudes and returns it at high latitudes. The different processes that affect this transfer, such as Ekman layer convergence and divergence, wind-driven and convective entrainment, stable detrainment, dynamic coupling between mixed layer and deep ocean, deserve further study and elucidation.

For short-term predictions (5 days) of the atmosphere, an interactive ocean model or ocean mixed layer model is not necessary, given accurate analyses of sea-surface temperature.

Short-term prediction of sea-surface temperature, mixed layer depth and subsurface temperature profile is a valuable goal in its own right for purposes of forecasting sound velocity distribution. Accurate predictions of this kind will depend on (i) accurate air-sea fluxes, and (ii) accurate sub-mixed layer specification.

Requirement (i) may be supplied from observational analysis or atmospheric prediction or a combination of the two.

Requirement (ii) likewise may be satisfied from observations of sub-mixed layer structure (e.g., XBTs, AXBTs, satellite altimetry, drogued drifters, drifting and moored thermistor chains) assimilated into an ocean model. The small scales of natural oceanic response (100 km) ought to be noted.

3. SENSITIVITY OF ATMOSPHERIC MODELS TO SST

3.1 Background

The goal of the workshop was to evaluate the potential of interactive ocean-atmosphere forecast models for operational applications. The discussion of forecast periods was limited to 3, 7, and 15 days. At these forecast times, it is appropriate to concentrate only on global atmospheric models, since regional models typically are not run beyond 48 hours. No effort was made to specifically concentrate on stand-alone parasitic-type planetary boundary layer (PBL) forecasts, since for forecasts exceeding 3 days the atmosphere must be considered an integrated system with the PBL and free atmosphere fully interacting.

The following discussion is organized around the 3-, 7-, and 15-day forecast periods and the three scenarios of the SASC report (Elsberry _et al_., 1982): They are (A) weak coupling, (B) nonsynchronous coupling, and (C) synchronous coupling and are defined in the Introduction.

3.2 Discussions and Conclusions

3.2.1 Three Day Forecast

This represents a minimum period over which SST sensitivity will have any significant influence on atmospheric model skill, and then _only_ when there is potential for significant SST time changes, such as during the spring and fall transition periods in the ocean. Interaction with the ocean is a second order effect when compared to the energetics associated with baroclinic processes and latent heat release in the atmosphere.

3.2.1.1 Weak Coupling. There is reason to believe atmospheric forecasts will be more accurate with an improved specification of the initial SST. There will be problems with climate drift in the SST's in data sparse areas because of biases in the ocean and atmosphere models. Improved global data coverage of SST and better quality control of SST analyses are necessary if the specified SST field is to improve the atmospheric forecasts. Diurnal variations in SST should be removed before use by the atmospheric model.

3.2.1.2 Nonsynchronous Coupling. In the mid-latitudes, there is reason for optimism if the qualitative behavior of time-dependent SST's is correct. Better forecasts of SST-sensitive PBL parameters such as fog and stratus should result. Forecasters might benefit from being more aware of predictions of SST change in the models and watch for its influence. In the tropics, however, lack of negative feedback from the atmosphere to suppress high-frequency noise in the predicted SST may excite anomalous tropical convection. Time and space filtering of SST fields should control this problem. Climate drift in the SST forecasts will be a problem, although it will not be as serious at 3 days as for longer forecasts.

3.2.1.3 Synchronous Coupling. In the mid-latitudes there will be little difference between synchronous and nonsynchronous coupling, since three days is too short a time for significant feedback between the models. In the tropics, synchronous is potentially superior to nonsynchronous because of the inclusion

of the negative feedback process, but this feedback will be very complicated and difficult to monitor and quality control. Therefore, filtering of high-frequency time and space scales in SST fields is still advisable, but diurnal variations should be retained.

3.2.2 Seven-day Forecast

At present, seven days represents the absolute limit of atmospheric model forecast skill. However, some 50% of the atmospheric forecast error is a non-random bias due to model climate drift during the forecast period. If this error can be significantly reduced, the seven-day skill should be comparable to the present three-day skill. Since this problem is the object of intense research at all major atmospheric modeling centers around the world, there is reason to expect considerable improvement within five years. This climate drift error is due to the model representation of terrain, stratosphere, and diabatic processes and is essentially independent of the specified SST. Therefore, it is unlikely that a no-skill, seven-day forecast will be improved by <u>any</u> type of atmosphere-ocean interaction.

3.2.2.1 Weak Coupling. If an improved SST specification is beneficial for three-day forecasts, it will also be beneficial at 7 days. Effects will be most pronounced during the spring and fall transition periods when the SST changes are large. However, since SST is held constant during the atmospheric forecasts, any atmospheric response to large SST changes during forecast periods will not be possible. This problem becomes more acute as the forecast period is extended.

3.2.2.2 Nonsynchronous Coupling. At seven days there is significant impact of tropical circulation systems on mid-latitude forecasts, so degradation of tropical forecasts due to an incorrect representation of SST, and especially its impact on tropical convection, cannot be tolerated. Time and space filtering of the tropical SST field is still definitely required. Care must be taken, however, to retain the signal in the SST field because of its interaction with the ITCZ and other major tropical convection features. Errors in the large-scale diabatic heating distribution in the tropics will have a definite impact on the mid-latitudes after seven days.

Large-scale errors in SST forecasts from an ocean mixed layer model are a distinct possibility with nonsynchronous coupling. Research with the use of "perfect prog" SST forcing is required to isolate atmospheric model dependent errors from SST-dependent errors.

3.2.2.3 Synchronous Coupling. The largest potential benefits, and conversely the maximum potential degradation (Elsberry et al., 1982), of forecasts is likely with a fully interactive atmosphere-ocean model. If negative feedbacks are modeled incorrectly, large-scale biases in both the atmosphere and ocean forecasts are likely. A fully interactive system will be very complex and difficult to monitor and quality control. Extensive testing and diagnostic studies of the feedback processes will be required, and the "perfect prog" SST forcing is essential to identify model dependent problems before full interaction is attempted. Forcing at the atmosphere model with SST fields including non-deterministic time and space scales must be avoided, and these scales must be identified.

3.2.3 Fifteen-day Forecasts

Numerical forecasts of 15 days will not be operationally feasible in the foreseeable future. Fifteen days is the theoretical limit of predictability in numerical weather prediction and only with a nearly perfect model can we expect to approach this goal. However, the interactive ocean-atmosphere problem must be solved before 15-day forecasts are feasible even with a perfect atmospheric model, because interaction with the ocean becomes a first order influence on forecasts of this length.

3.2.3.1 Weak Coupling. With SST forcing being an important factor after 15 days of forecast, holding SST constant for this period makes the success of this option highly unlikely, particularly during the spring and fall transitions.

3.2.3.2 Nonsynchronous Coupling. This scenario is impractical, since imperfect models of either ocean or atmosphere will develop biases which will overwhelm the forecasts by 15 days. "Perfect-prog" application in a research mode is the only useful application of this approach.

3.2.3.3 Synchronous Coupling. If a 15-day forecast capability is ever to be achieved, it will have to include a fully interactive ocean mixed layer/atmosphere model. A possibility with such a system is that the ocean mixed layer, which is inherently more predictable than the atmosphere, may retain forecast skill even after the atmospheric model has lost any useful skill. This is contingent on the atmospheric model providing a reasonable climatological forcing and having good time-averaged behavior. Time-averaging of the SST forecasts will be necessary to remove the influence of non-deterministic, high frequency atmospheric forcing.

A necessary condition for the success of the 15-day forecast is the successful performance of an interactive ocean-atmosphere system at seven days. It is inconceivable that an interactive system that has no skill at seven days could have useful skill at double that forecast period.

3.2.4 Overall Conclusions

Table 1 summarizes the overall conclusions.

Table 1. Overall conclusions.

Coupling	3 Days	7 days	15 Days	Summary
Weak	Yes, But Need 1) Quality SST 2) Remove diurnal SST	Probably Yes but impact of constant SST unknown	No	Best application for 3-day forecast
Non-Synchronous	Yes - For Midlatitudes No - In Tropics Overall - Unlikely	No - Degradation in tropics will overwhelm forecast	No	Not good option for any time scale Good research tool
Synchronous	Ultimately Yes 1) Retain diurnal SST 2) Must understand interaction	Ultimately Yes Only after interaction understood	Ultimately Yes 1) Only after atmospheric models improve	Ultimately best option particularly for 7 & 15 days
Summary	Weak Coupling best for present Synchronous Coupling ultimately best	Most unknown time scale	Synchronous is only hope	

3.3 Recommendations

3.3.1 Implement Weak Coupling As Soon As SST Analysis Can Support It.

A better SST analysis than is currently being operationally produced is necessary to support interactive ocean-atmosphere model development. The heavy climatological influence in the present SST analysis must be reduced. This SST improvement depends on both the data assimilation process (TOPS/EOTS) as well as expanded data. Atmospheric models cannot tolerate anomalous SST's arising from biases in the mixed layer model forecasts which may occur in data-void areas as the data assimilation cycle proceeds. This means vigilant quality control is required to identify these areas and manual intervention in the analysis process if necessary.

The present operational SST observation data base is probably inadequate unless all available satellite observations are used. Full global coverage is also a necessity, since both the atmosphere and ocean models will be global. This implies at least two polar orbiting satellites to give adequate temporal as well as spatial resolution. Horizontal resolution of the SST fields needs only be equivalent to atmospheric model resolution (1o-2o). Other fleet requirements for the SST fields have more stringent resolution requirements, although these are in specific operating areas rather than on a global basis.

Without a reliable, high-quality, SST data assimilation system such as TOPS/EOTS, there is little hope for an operational interactive ocean/atmosphere forecast system. The initial SST analysis must be assumed to be an accurate representation of the real ocean so that SST forecast errors are essentially model dependent and not the result of errors in the initial data.

3.3.2 Study Interaction Extensively Before Proceeding to Synchronous Coupling

It would be unwise to proceed directly to a synchronous system without extensive research using a form of nonsynchronous coupling in which the atmospheric model is rerun on a delayed basis with the observed SST values rather than the forecast values (i.e., a perfect-prognosis of the SST). During this research and development stage, there will be much more control and one can closely monitor the model performance. By contrast, a fully interactive system will be so complicated that diagnosis of the cause of forecast errors during the developmental stage might be impossible. A synchronous system should only be tested when the perfect-prognosis form of the nonsynchronous system has been fully developed and the interactive ocean atmosphere model performance characteristics are completely understood. This is true even if the perfect-prognosis nonsynchronous system suffers from errors which degrade its forecast to the point of no skill, as will probably be the case for longer forecast periods (7-15 days). If the reasons for the errors are understood, then special attention can be paid to these when the synchronous system is evaluated.

It must be emphasized that for three- and even seven-day forecasts the influence of changing SST's on an atmospheric forecast model will be quite subtle, since many atmospheric circulations are quite insensitive to the underlying boundary conditions on temperature. There will be certain circumstances (e.g., explosive cyclogenesis), however, when differences in SST may have significant influences on model forecasts. To properly evaluate either a synchronous or nonsynchronous coupled system (compared to a control system using some form of weak coupling), a very large number of forecasts must be run to generate a statistically significant sample of the cases showing differences between the control and test system. This implies a considerable expenditure of manpower and computer time.

3.3.3 Use Case Study Approach

As mentioned in 3.3.2, a case study approach to evaluating the performance of an interactive ocean-atmosphere forecast system is essential. Some method of _a priori_ picking those forecast cases exhibiting sensitivity to SST would be extremely useful. This would eliminate the need to run a very large number of forecasts and then picking only those which are of interest. Considerable computer resources could be saved because it is much more expensive to regenerate the initial conditions necessary for an atmospheric model than it is to simply schedule that extra run as a part of the regular operational run.

When a suitable number of SST sensitive cases can be collected, these should serve as the basis for subsequent tests and evaluation of nonsynchronous or synchronous forecast systems.

3.3.4 Isolate Climate Biases

To identify climate drift biases in the atmospheric model a long term simulation should be run to define the model's climatology. Climatological SST values should be used in these tests to isolate model biases due to other effects. Whenever major changes are made to the model's diabatic processes, the simulation should be repeated to document the impact on the model climatology. When interaction with the ocean is introduced, such simulations will again be necessary to identify any new climate drift biases in the coupled system.

Such simulations are clearly part of a basic research effort and will undoubtedly take place at several atmospheric research facilities during the next several years. Operational centers should support these efforts and monitor their results to assess when enough progress has been made to warrant similar experiments with operational models.

3.3.5 Development of Operational Models Should Concentrate on Other Error Sources Before Proceeding with SST Coupling

With current operational atmospheric models, the influence of SST on forecast quality is secondary in importance to the effects of model resolution and the influences of smooth topography, in complete model dynamics, and errors arising from the parameterizations of the planetary boundary layer and latent heat

release. Only when atmospheric models can produce reliable forecast for seven days and beyond will the influence of time-dependent SST become comparable to these other processes. On a cost effective basis it is therefore recommended that research efforts with operational models concentrate on reducing the errors due to these other factors before the interactive ocean-atmosphere model is attempted. Basic research efforts on the interactive problem are recommended, following the guidelines proposed above.

4. SENSITIVITY OF OCEANIC MODELS TO ATMOSPHERIC FLUXES OF MOMENTUM AND HEAT

4.1 Background

In this section we will evaluate the impact of the various stages of atmosphere-ocean model coupling on the behavior of the oceans. Because of the peculiar hydrodynamic-thermodynamic response of the ocean to the atmospheric forcing fluxes, with a resultant large separation of scales between mixed layer and ocean gyres, we need to discuss the coupling influence not only in terms of three scenarios as described in the introduction, but in terms of mixed layer response and large-scale dynamic circulation as well.

4.1.1 Scenarios

As in the atmospheric discussions, we will need the definitions defined in the introduction repeated here to remind the reader.

Weak Coupling. SST held constant during the forecast period with interaction only weakly through the update cycle of atmosphere model and SST analysis-forecast model (NOGAPS and TOPS/EOTS in Navy configurations);

Nonsynchronous Coupling. Atmospheric model is provided a time-dependent SST during the forecast period as a result of non-interactive SST forecast. Feedback between the ocean and atmosphere occurs only through the update cycle; and

Synchronous Coupling. Fully interactive coupling during the forecast period of both models.

4.1.2 Oceanic Features

We will also need definitions for the following oceanic features:

(1) Mixed Layer: The upper 50-150 m of the world's oceans where strong coupling to atmospheric momentum and heat fluxes results in a uniform temperature distribution;

(2) Seasonal Thermocline: The gradually decreasing temperature region below the mixed layer that responds to the seasonal variation of winds and heat fluxes;

(3) Oceanic Front: A sharp boundary between water masses of different temperature and/or salinity, caused either by hydrodynamic, thermodynamic or combined processes;

(4) Mesoscale Eddies: The baroclinic "cyclones" of the ocean, on scales of 150-400 km or so, at depths of 200-1000 m and time scales of 3-18 months;

(5) Large-Scale Currents and Gyres: Typical examples are the Gulf Stream, Kuroshio, equatorial currents, and their associated loops, shed rings, also mid-oceanic gyres. These currents are generally established by the climatological wind curls over the oceans but then proceed to have dynamical instabilities independent of the forcing.

The coupling between these various oceanic regions/features is generally loose. The coupling between (1), (2) and (4), (5) is generally one-way on time scales of our interest; eddies and currents advect the mixed layer and seasonal thermocline, with almost no feedback on time scales of 15 days or less. Oceanic fronts that reach the surface will be influenced by the mixed layer's behavior.

4.2 Discussion and Conclusions

The prediction of the mixed layer and seasonal thermocline will depend on predictability of the synoptic/seasonal behavior of the atmosphere. The main impact of the ocean on the atmosphere occurs via the magnitude and distribution of SST. Changes in SST are related to mixed layer depth and heat content of the layer, and can be caused by vertical mixing, upwelling or horizontal advection. The prediction of vertical mixing, Ekman suction and Ekman advection are closely coupled to prediction of the atmospheric momentum and heat fluxes. The prediction of vertical and horizontal geostrophic currents depends on the prediction of dynamic ocean features such as Gulf Stream, mesoscale eddies, etc. and on the time scale of 15 days or less, only little dependent on atmospheric prediction. We will discuss the time problems separately below.

4.2.1 Mixed Layer Coupling

The hydrodynamic/thermodynamic responses of the mixed layer generally lag behind the atmosphere by a time interval approximately one day or less, and involve the inertial mechanisms. Any improvement in the prediction of the atmosphere results in an immediate improvement in the prediction of SST and MLD, i.e., mixed layer prediction would benefit from all three scenarios. So far no results have been published on coupled air-sea interaction experiments on time scales of 15 days or less, so that the relative merits of the three scenarios cannot be assessed

quantitatively at this time. However, any long term bias in the atmospheric forecasts will have serious consequences for the mixed layer. Long term bias in wind prediction will not cause great problems, because turbulence dissipation and the Coriolis force limit the depth of momentum penetration, but a bias in the heat flux will lead to anomalous heat content of the MLD that eventually will be fed back to the atmosphere. Thus if weak coupling is implemented, then in cloud-covered areas or in regions of no XBT information, the SST analysis coming from the TOPS/EOTS analysis must be carefully quality controlled to correct this bias if it develops.

The surface position of fronts can be displaced by atmospheric fronts via inertial mechanisms, but these displacements are generally small and the total area of affected oceans is not expected to be significant for atmospheric prediction, though these displacements may be important for regional ocean prediction.

4.2.2 Dynamic Circulation Prediction

The response of the large-scale oceanic circulation to changes in wind stress occurs via Kelvin and Rossby waves whose time scale is on the order of months. On time scales of 1-15 days, therefore, almost no impact of the improved atmospheric forecast will be felt. Changes in Gulf Stream position, for example, are due to a dynamical instability of the stream, almost independent of the atmospheric forcing, and the expected coupling will be from ocean to atmosphere. In the expected scenario on ocean forecasting at FNOC, a prediction of ocean currents and

eddies will be made up to 60 days in advance, without the use of atmospheric prediction; the results will provide advection currents that displace fronts and eddies. The areas affected by these displacements can be sufficiently large over a 7-15 day period to affect atmospheric prediction. Strong changes in SST can occur in areas of large scale upwellings, e.g., west coast of the American Continent, caused by changes in wind and the corresponding along-shore currents. Whereas these changes can occur on time scales of 3-15 days, upwellings in equatorial regions have time scales of months.

4.3 Recommendations

(1) Implement weak coupling as soon possible for all time scales of prediction to improve SST and MLD prediction. The remarks concerning SST analysis from TOPS/EOTS and satellites will also apply here;

(2) Nonsynchronous coupling (ocean driving atmosphere) should be implemented as soon as products of a dynamic ocean forecast model are available, to allow for horizontal advection of fronts, rings and eddies. Note that this is distinct from the coupling between the atmospheric and mixed layer model, which is not recommended.

(3) Nonsynchronous coupling (atmosphere driving ocean) should be implemented in ocean regional forecasts containing upwelling areas.

(4) Studies should be carried out to evaluate the impact over a 15 day period of synchronous coupled prediction on mixed layer response.

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APPENDIX A

WORKSHOP

COUPLED OCEAN-ATMOSPHERE MODELING FOR NUMERICAL PREDICTION

30-31 AUGUST 1982

Monterey, California

PROGRAM

30 August 1982

0830 Welcome - A. I. Weinstein (NEPRF)

0900 Administrative Details - G. Gold (NEPRF)

0915 SESSION 1 - STATUS OF NAVY MODELS - Chairman, T. E. Rosmond

- 0915 - Navy Atmospheric Prediction Models - T. E. Rosmond (NEPRF)
- 0945 - Navy Thermal Ocean Prediction Model - M. Clancy (NORDA)
- 1015 - BREAK
- 1030 - Preliminary Report on Navy World Ocean Primitive Equation Model - G. Heburn (NORDA)
- *1100 - Ocean/Troposphere Forecast Systems: A State-of-the-Art Review (NEPRF CR 82-04) - R. L. Elsberry (NPS)
- 1130 - LUNCH

1300 SESSION 2 - RESEARCH RESULTS - Chairman, S. Piacsek

- 1300 - Ocean Thermal Response to a Global Sector Atmospheric Numerical Model - S. A. Sandgathe (NPS)
- 1330 - Use of Satellite Derived SST's in NWP - R. L. Haney (NPS)
- 1400 - Sensitivity of National Meteorological Center Models to SST - J. B. Hovermale (NMC)
- 1430 - Interactive Ocean - Atmosphere Modeling at the National Center for Atmospheric Research - R. A. Anthes (NCAR)
- 1500 - BREAK

*During the workshop, this presentation was delayed until after lunch. Each afternoon presentation was therefore delayed by 30 minutes.

1530 - Preliminary Experiments with the Goddard Laboratory for Atmospheric Science Coupled Ocean-Atmosphere Model - E. Kalnay (GLAS)

1600 - Results of the Oregon State University Interactive Ocean-Atmospheric Model - Y. J. Han (OSU)

1630 - Modeling of Horizontal Structure in Ocean Mixed Layers - R. DeSzoeki (OSU)

1800 ICE BREAKER - Naval Postgraduate School, La Novia Terrace

31 August 1982

0900 - Concurrent Working Sessions

Ocean Modeling

Atmospheric Modeling

1200 - LUNCH

1330 - PLENARY SESSION - Chairman, A. I. Weinstein

1330 - Introduction

1345 - Ocean Modeling

1415 - Atmospheric Modeling

1445 - Discussion/Review

APPENDIX B

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